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January 4, 2023

Dear Friends,

The Healthy Soils Action Plan (HSAP) is a very important document because it is the first time that the value of the soil has been highlighted and explained and a menu of achievable action steps outlined from which options can be selected for improving our soil health – the foundation for all our ecosystems and life in our forests, farms, wetlands, and green spaces near us. The HSAP is the first such plan in the nation that focuses on all land cover types – farms, forests, wetlands, lawns and developed land. It is this holistic approach that is a key strength of the plan.

The soil that covers the five million acres of the Commonwealth is the foundation for our food, our forests, our drinking water, and the biodiversity of our many unique ecosystems. The quality of our soil is also increasingly important in helping us to adapt to the impacts of climate change because our soils regulate water quality, flooding, heat islands, drought response, and the productivity of trees and forests and farm crops. The good news is that though our soils have been significantly degraded over many decades; there are steps we can take to significantly protect and restore them. The 2020's are the decade to focus on reducing impacts from climate change and restoring our ecosystems, and it all begins with our soil. This is also the decade where we must bring social justice to our natural resource decisions, including the health of nearby soils.

Dozens of meetings with soil experts, land managers, farmers and foresters, planners and advocates have resulted in a plan that is based in science and research and one which realistically looks at a wide range of actions to improve our soils and the ecosystems that rely on them. Whether you are a farmer, a forest landowner, a resident with a small yard or a municipal planner; there are recommendations in this plan of which you can be a part. This plan shows the importance of our soils and the value of protecting, restoring and caring for them and the many benefits to our residents from taking these steps.

The Executive Office of Energy and Environmental Affairs looks forward to working with the many healthy soil stakeholders to move ahead on the priority recommendations of this important plan.

Sincerely,

Bethany A. Card, Secretary

The Massachusetts

Healthy Soils Action Plan

Regenerative DesignGroup
LINNEAN Solutions
NOFA MASS
Perennial Solutions

The Massachusetts Healthy Soils Action Plan | 2022

Table of Contents

Index of Figures, Maps, and Tables

Acknowledgements

Perennial Solutions

The **Massachusetts Healthy Soils Action Plan** was prepared over an 18-month period for the Executive Office of Energy and Environmental Affairs under the direction of Tom Anderson and Bob O'Connor and with support from the Massachusetts State Commission for Conservation of Soil, Water & Related Resources.

This plan was developed in collaboration with a dedicated Working Group comprised of resources managers and conservationists, researchers, and agency representatives with a variety of expertise. The process included 14 stakeholder meetings and three public comment sessions. The research, analysis, interviews, and writing were conducted by the Project Team.

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Executive Summary

CONTEXT

The Massachusetts Healthy Soils Action Plan—a plan to protect, restore, and better steward soils across the Commonwealth—comes at a critical time. In March of 2019, in recognition of the twin emergencies of climate change and ecosystem collapse, the United Nations General Assembly declared the decade between 2021 and 2030, "The Decade of Ecosystem Restoration." This call to action recognizes that intact and thriving ecosystems are essential for clean air and water, biodiversity, food security, public health, and adaptation to a warming planet.

The work of protecting, restoring, and stewarding the Earth's ecosystems—its forests, oceans, inland and coastal wetlands, farmlands, grasslands, and soils—needs to happen at all scales, from international collaboration to municipal level decision-making. Of course, it is not only natural and working lands that need protection, restoration, and stewardship during the coming decade and beyond. Developed landscapes in our cities and towns, as well as abandoned relics of development like brownfields, are ecosystems in dire need of nature-based solutions that prevent and repair losses to ecosystem function.

It is this attention to both natural and working lands and developed landscapes that makes the Massachusetts Healthy Soils Action Plan (HSAP) unique among the important healthy soils initiatives begun by other States in the last decade, many of which have largely focused on agriculture. To be sure, reversing the astonishing loss and degradation of agricultural soils is a vital part of ecosystem restoration. But for Massachusetts, which is largely characterized by forest cover and ever-expanding development, it is vital that we look at the potential of all soils to support biodiversity, healthy watersheds, and climate adaptation—not for the Commonwealth alone, but as a model for others.

KEY FINDINGS

The HSAP assesses and makes recommendations for five major land covers of the Commonwealth: Natural and Working Lands includes Forests, Wetlands, and Agriculture, while Developed Landscapes include Recreational/Ornamental and Impervious/Urbanized Lands. The project team sought to understand threats and opportunities to soil health through the three lenses of Land Conversion, Climate Change and Natural Hazards, and Soil Management, and make recommendations consistent with those findings. Additionally, because carbon content is one of the few universally agreed-upon indicators of soil health and can be assessed at a coarse scale, there are findings and recommendations that speak specifically to protecting and enhancing soil organic carbon within the five land covers.

Preventing net loss of forests and wetlands—which together make up 64% of the state's land cover—is key to preserving the vital soil and other ecosystem functions of those landscapes. Even from a strict carbon drawdown and storage perspective, the value of Massachusetts forests and wetlands compared to other land covers are unmatched in their importance for mitigating and adapting to climate change. But protection is only a starting point. Centuries of soil degradation, coupled with natural hazards and climate change, necessitate financial and technical support for soil restoration and ongoing soil-smart management.

It is also important to recognize that when determining which policies and programs to pursue to protect and enhance soils the Commonwealth will need to carefully balance the preservation of undeveloped land and the restoration of soil on disturbed sites with the need to accommodate housing production and other new development. Ultimately, good soils practices are critical not only on natural landscapes, but also when building or redeveloping sites for needed housing and economic development.

Prioritizing protection of agricultural lands is also vital. Although this land cover is the smallest of the five HSAP categories at 4% (205,405 acres), this category is of critical importance for ensuring local and regional food security. This will continue to be the case with increased impacts of climate change and other disruptions like global pandemics. Yet again, protection of agricultural lands and their soils is a starting point.

Farmers need long-term support that increases the viability of farming as a livelihood and incentivizes and rewards soil-smart practices.

The two HSAP categories of Developed Landscapes—1. Recreational and Ornamental land cover, and 2. Impervious-Dominated land cover—account for 20% (nearly a million acres) of total land cover in Massachusetts. Without a change in development patterns and population trends, this category will continue to grow, though predictions vary widely, ranging from around 30,000 acres in the 2050 Decarbonization Roadmap to more than 300,000 acres in some of the New England Land Futures scenarios. These landscapes present unique challenges for protecting and regenerating soil function. Unlike natural and working lands, the main driver of soil health in developed lands is the development process itself, rather than management practices. Conventional development practices result in the removal of most or all of the upper soil horizons and the vegetation that once grew there. This disturbance dramatically alters both the intrinsic and the dynamic soil properties. Developed soils typically lose 25 to 60 percent of their total soil organic carbon and have a thin, compacted 'top soil' unsuitable for robust plant growth or proper stormwater infiltration. Once development is completed, management can play a crucial role in the health of these soils, but only within the narrow margins of the new soil's dynamic properties.

The impacts of climate change, notably more frequent high-intensity rain events, amplify the challenges of diminished soil function in these landscapes. The disturbance and replacement of the A and B Horizons of native soils (which may be up to 31″ deep in the case of Paxton Silt Loam, the Massachusetts' State Soil) with a 4-6″ layer of 'loam' over compacted subsoil results in a significant loss of the native soil's water infiltration, filtration, and water holding functions. With this loss of soil function, engineered stormwater solutions become necessary.

Priorities for improving soil health in developed lands include addressing post-construction soil performance; increasing protection of soil, topography, and vegetation during construction; expanding green infrastructure, including tree-planting; and cleaning up contaminated soils.

CONCLUSIONS

Simply put, healthy soils are soils capable of supporting healthy ecosystems and the services they provide. This inexorable connection between the soil capabilities and ecosystem functions makes the stewardship of soil resources essential to every citizen of Massachusetts by offering win-win solutions which increase both economic and ecological yields of living landscapes.

Soil Organic Carbon (SOC) concentrations in the top 100-cm is both a primary measure of dynamic soil health and a key mechanism for improving soil function. The land management and development recommendations described in this Healthy Soils Action Plan are largely based on the fact that dynamic soil properties generally improve when there is less disturbance to soils and their plant communities. This time allows the carbon-rich substances captured from the atmosphere by plants to develop into soil organic carbon (SOC). This increase in SOC improves both the availability and holding capacity of both nutrients and water, creating a beneficial feedback system where increased soil health builds overall ecosystem productivity resulting in even greater soil capabilities.

In this time of climate-destabilizing atmospheric carbon concentrations, this relationship between soil health and carbon mean many of the soil-smart recommendations also support the myriad existing plans and initiatives aimed at addressing community vulnerability and resilience to the unprecedented social, economic, and ecological conditions of our time.

Massachusetts Healthy Soils Goal

In alignment with the bold goals of the Massachusetts Decarbonization Roadmap, the Clean Energy and Climate Plans for 2025/2030 and 2050, and the Resilient Lands Initiative, the Healthy Soils Action Plan offers a single goal—**no net loss of Soil Organic Carbon between 2021 and 2050.**

Massachusetts Healthy Soils Strategies

This goal encompasses seven soil and land use related strategies identified as priorities by the Healthy Soils Working Group. These consist of:

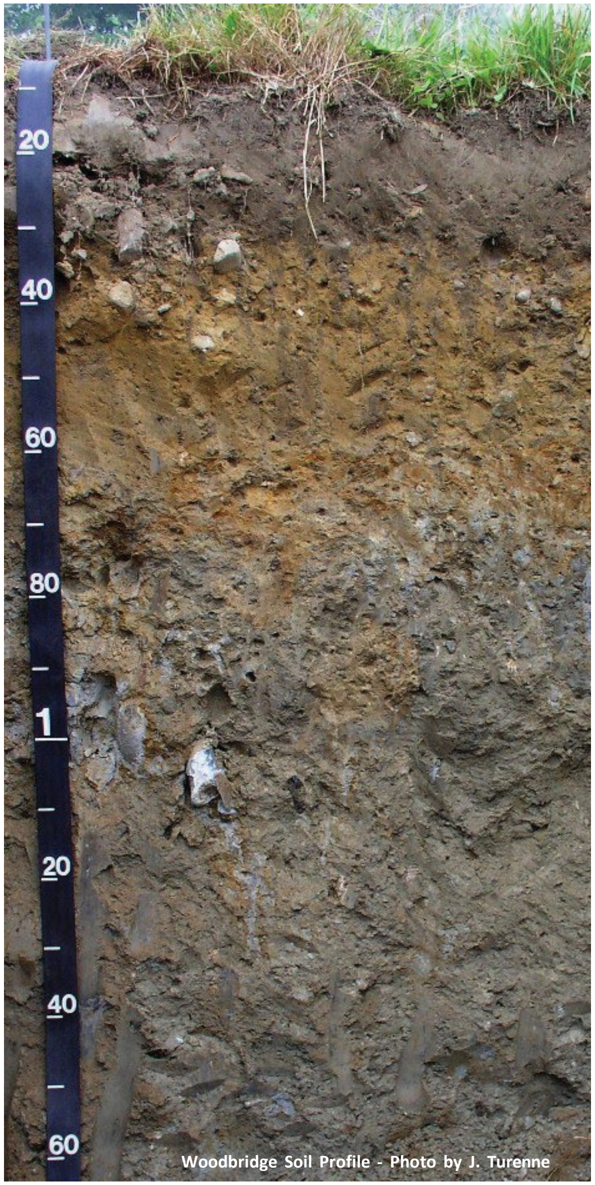
- Limit the conversion of Forests, Wetlands, and Farmlands;
- Enhance the functional capacity of soils across all land covers;
- Transform development-related soil management practices;
- Account for Soil Organic Carbon Pools + Sequestration Capacity in all carbon accounting efforts;
- Expand technical, financial, educational, and material support for land managers of all types to employ soil-smart practices;
- Incorporate soil-based criteria into state and municipal legal and financial mechanisms that influence land use and land management practices; and
- Enhance the analytical capacity for measuring and monitoring soil health in Massachusetts.

Massachusetts Healthy Soils Actions

Among the many actions recommended in the Healthy Soils Action Plan, there are six that have been identified as highest priority:

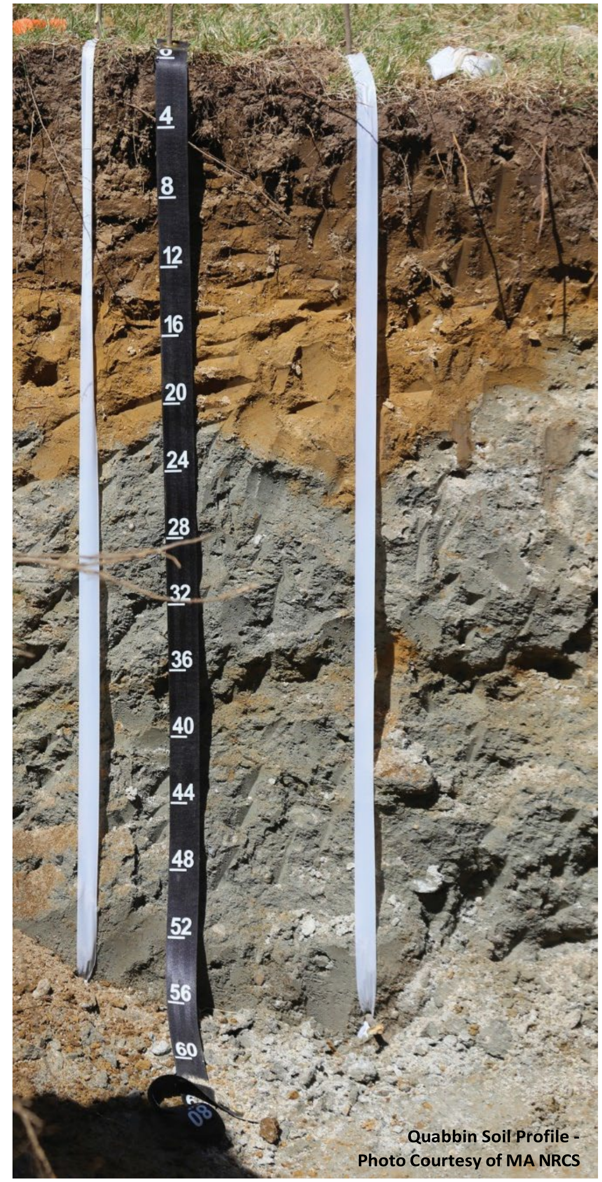
- Seek to protect healthy forested soils through strategic conservation of additional forest parcels (page 45).
- Increase and adapt active forest management practices to bolster resistance to degradation from and resilience to climate change (page 46).
- Consider ways to increase preservation of existing soil organic carbon stocks and sequestration capacity, potentially including updates to the Wetlands Protection Act (page 62).
- Enroll 50% of existing agricultural production acres in the implementation of soil health plans by 2030 (page 78).
- Continue funding the Healthy Soils Pilot Program that exemplifies healthy soil practice in developed landscapes (page 96).
- Consider developing Post-Construction Soil Performance Guidelines focused on water quality, drought resistance, stormwater runoff, soil depth, and carbon content for all site development + construction projects (page 103).

The Healthy Soils Action Plan for Massachusetts is the first of its kind. By endeavoring to protect, manage, and regenerate soil health across a diversity of ecosystems, land uses, and soil types, this plan lays the groundwork for other states to follow. The coming years will require determined and strategic action from lawmakers, land managers, and program administrators to shape effective action with the support of research institutions and observant practitioners. Municipalities, agencies, and institutions are encouraged to engage with these recommendations and downscale the findings to their places, people, and soils.



Woodbridge Soil Profile - Photo by J. Turenne

Urban Soil Profile - Photo Courtesy of MA NRCS



Quabbin Soil Profile - Photo Courtesy of MA NRCS

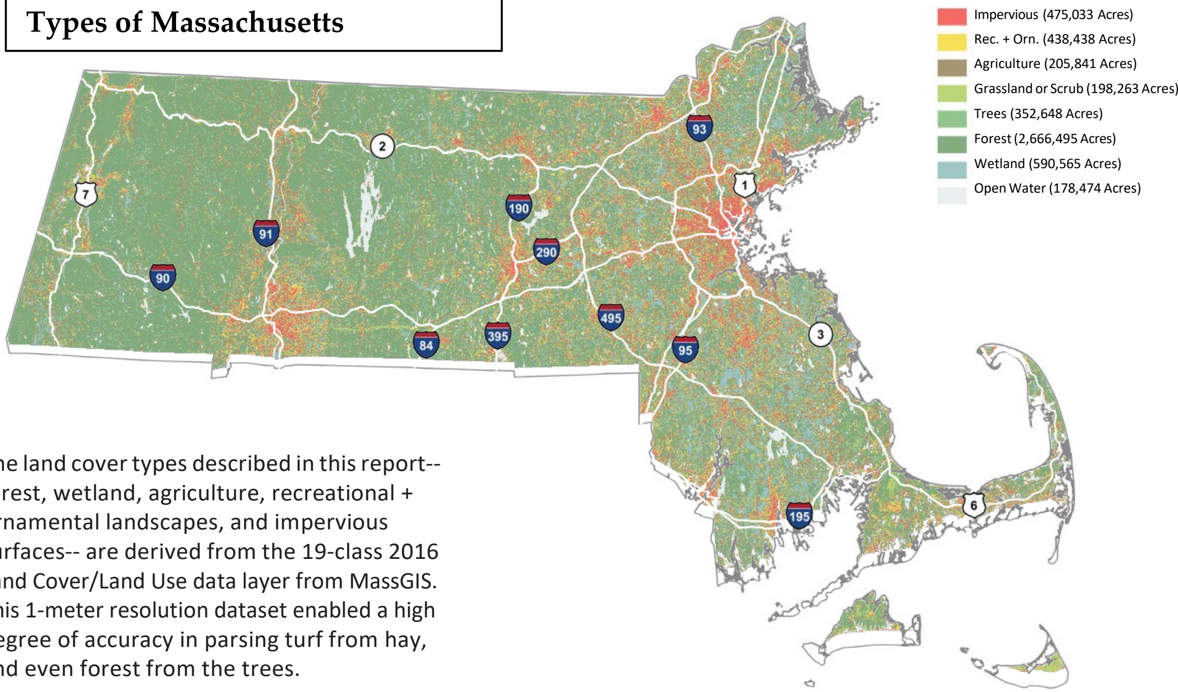
Soil horizons are the layers that develop during the soil-forming processes through the interaction of the climate, organisms, relief, and parent material over time. Human activities, such as those associated with urbanization and agriculture, can radically influence these processes and the resulting soil profile. The large pieces of concrete visible at 70cm in the urban soil profile (*center*) illustrates this clearly.

01 | Introduction

Vision and Goals

The purpose of the Massachusetts Healthy Soils Action Plan is to provide evidence-based recommendations that help people better protect, restore, and manage soils of five major land covers: Forests, Wetlands, Agriculture, Recreational and Ornamental Landscapes, and Impervious and Urbanized Lands. The recommendations in this report propose a coordinated approach for protecting the diversity and productivity of our natural and working lands; assisting cities and towns in building resilience to natural hazards and climate change; and achieving the ambitious and necessary goals of the Global Warming Solutions Act.

Map 1.1 – Major Land Cover Types of Massachusetts



The land cover types described in this report--forest, wetland, agriculture, recreational + ornamental landscapes, and impervious surfaces-- are derived from the 19-class 2016 Land Cover/Land Use data layer from MassGIS. This 1-meter resolution dataset enabled a high degree of accuracy in parsing turf from hay, and even forest from the trees.

A Critical Moment

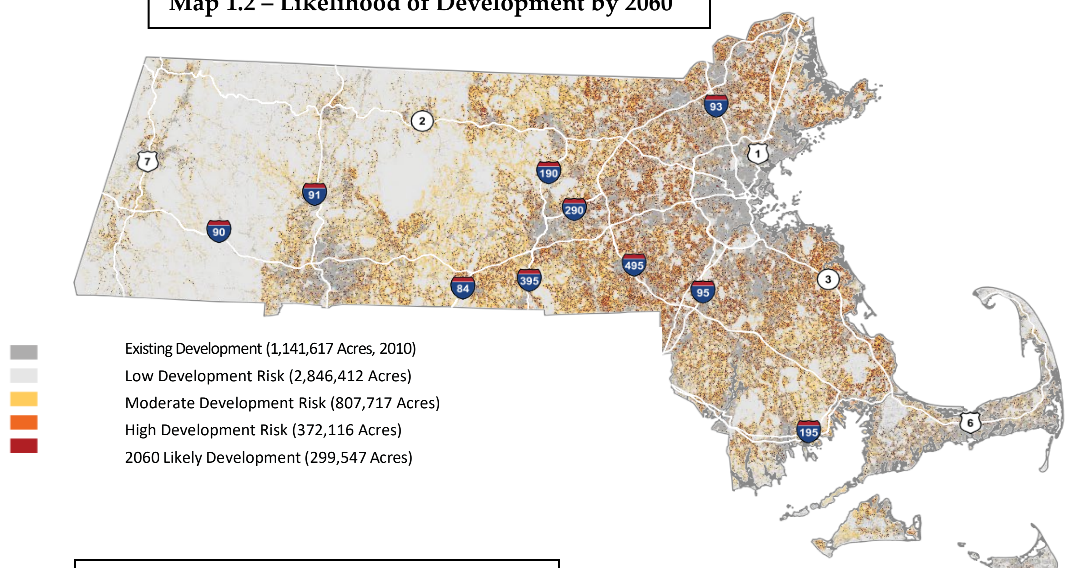
Healthy, living soils are the foundation of the ecosystems that nurture and sustain people and all life, shape the character of our communities, support the livelihoods of farmers and foresters, and underpin the rich diversity of life in Massachusetts. The health of soils and their performance are strongly influenced by their land use history, current land cover, and how they are managed. Protection, restoration, and optimal management of soils are essential for water quality, biodiversity, food production, healthy plant communities, and carbon sequestration. Preserving and enhancing these vital functions are necessary for averting ecological and climate disaster scenarios and will help us mitigate and adapt to the unavoidable changes brought on by a warming climate. In the coming decades, Massachusetts can expect increased severity and duration of rain and drought, sea level rise, warmer temperatures, and extreme weather. These trends all pose risks to natural and human communities of the Commonwealth, our built environments, governments, and economies (MA State Hazard Mitigation and Climate Adaptation Plan, 2018).

Land Consumption and Soil Degradation

The conversion of land from forests, fields, and wetlands to building lots and lawns significantly diminishes the health of soils. Strategic development and bold land use planning actions with regard to soil health, however, can help reduce conversion of land, mitigate the intensity of climate change, and meet goals like those set forth in the Decarbonization Roadmap and the Clean Energy and Climate Plans.

This loss in soil function occurs from the removal of trees and other plant communities, which act as soil carbon generators, as well as through changes made to the physical structure of the soil. To date, of the 5.18 million acres of soil in MA, 475,033 acres (9.2%) have been converted to buildings and pavement in which case almost all of their vital function has been lost. Some of this acreage includes sites with active hazardous material contamination in their soils. A composite analysis of the New England Land Futures development scenarios suggests as many as 372,116 additional acres (7%) have a high vulnerability to conversion by 2060. (**Map 1.2**) According to a 2020 study on land consumption from Harvard Forest, the majority of future development is likely to occur on forested lands (Thompson et al, 2020). The conversion of forests to developed lands like houses, pavement, and turf has long term negative impacts on soil functions such as stormwater infiltration, soil biodiversity, and soil organic carbon (SOC) storage. For instance, soils lose 54% of the average forest SOC stock when converted to turf and 74% when converted to impervious land covers (HSAP SOC Study).

Map 1.2 – Likelihood of Development by 2060

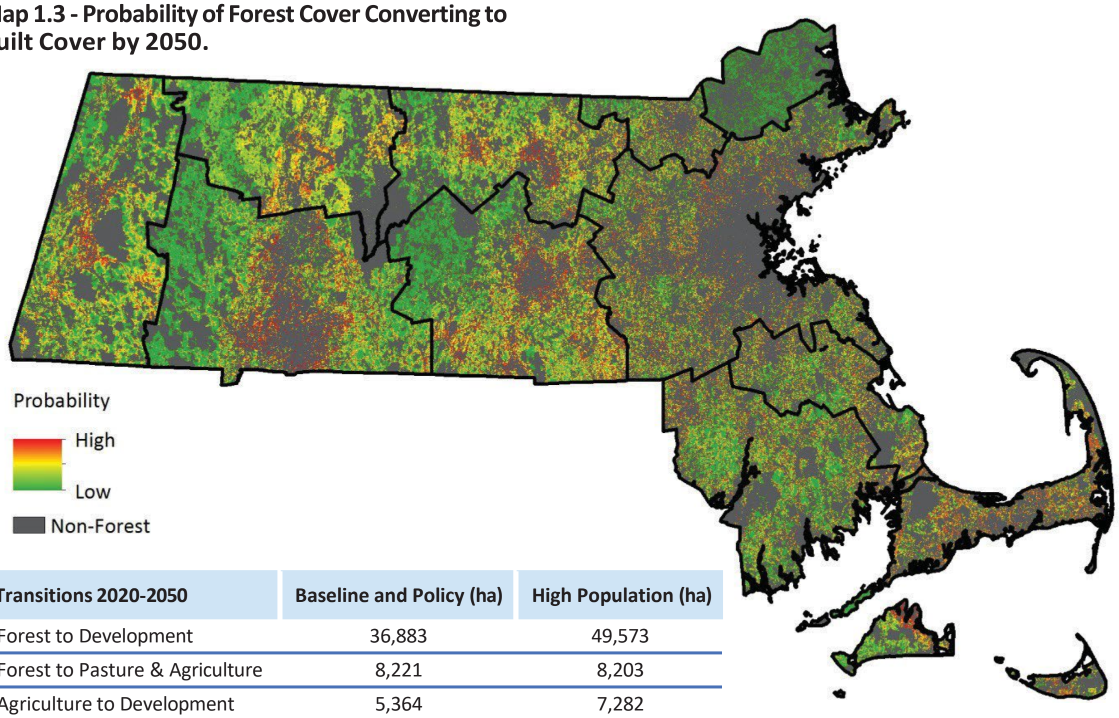


Development pressure was calculated by considering which of the New England Land Futures five land use change scenarios showed development by 2060. Scenarios in which development appeared in three or more scenarios are High Development Risk; in one to two scenarios are Moderate Development Risk; and in zero scenarios, Low Development Risk. The 2050 Likely Development areas are classified by the NELF Recent Trends report as Newly Developed by 2050.

The total estimated loss from land cover change for the year 2060 alone is 245,000 tons of soil organic carbon, or 900,000 tons of carbon dioxide. Measured against the 1990 benchmark for the No Net Carbon Emissions goal from the Decarbonization Road Map, the loss of this SOC would add an additional 1% to total annual emissions.

In order to help avoid these carbon emissions and mitigate the intensity of climate change, this report outlines recommendations necessary to accomplish the Commonwealth's goals. For example, limiting and mitigating the development of natural and working lands in 2060 by continuing to explore land use policies and incentives to encourage redevelopment of under-utilized sites, steer new development to infill locations, and minimize the loss of natural and working lands would help close the gap to achieving Net Zero Carbon emissions by almost 2%.

Map 1.3 - Probability of Forest Cover Converting to Built Cover by 2050.



Transitions 2020-2050	Baseline and Policy (ha)	High Population (ha)
Forest to Development	36,883	49,573
Forest to Pasture & Agriculture	8,221	8,203
Agriculture to Development	5,364	7,282
Agriculture to Forest	1,100	1,097
Other to Development	4,084	5,644
Other to Forest	4,917	4,916

Map and Table from Thompson et al, "Land Sector Report, A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study"

A Seedbed for Change

Employing these soil smart actions has the potential to protect and grow the health of soils, while also assisting a number of the existing initiatives aimed at building economic and ecological resilience across the Commonwealth.

For example, limiting forest, wetland, and farmland conversion aligns with the Net Zero Forest and Farms Loss goals of the Resilient Lands Initiative and the carbon emissions reduction goals required by the Decarbonization Plan.

By employing healthy soil practices, land managers have the potential to increase annual soil organic carbon sequestration rates. In the year 2050, this annual increase could range from a modest gain of 18,000 metric tons to as much as 128,000 tons of SOC. Equal to 473,000 tons of carbon dioxide, this higher sequestration rate helps close the gap by 3.34% toward the no-net carbon emissions goal of the Decarbonization Roadmap.

The UN has declared the current decade, 2021 to 2030, "The Decade of Ecological Restoration", coinciding with the window—ten years at best—to change the planet's current ecological and climate trajectories. The HSAP project team and Working Group believes that this effort can do much for Massachusetts and beyond, as a model for innovative, practical response. Protection and restoration of biodiversity and ecosystems, beginning with soils, coupled with real progress in reducing carbon emissions from fossil fuel extraction/combustion and land alteration, will be critical to true sustainability.

This Action Plan draws from and seeks to integrate with the considerable state and region-wide initiatives already tackling landscape scale conservation and restoration, food systems, working lands, and climate adaptation and mitigation efforts. Mass Audubon's Losing Ground Series, New England Landscape Futures, Wildlands and Woodlands, and the MA Roadmap (formerly 80x50) have all informed the strategies and framing found within this document.

Additionally, the project team drew from and sought to reinforce or align with recommendations found in:

» The Massachusetts 2050 Decarbonization Roadmap;

» The 2025/2030 and 2050 Clean Energy and Climate Plans;

» The Massachusetts Resilient Lands Initiative;

» The Massachusetts 2018 State Hazard Mitigation and Climate Adaptation Plan; and

» Massachusetts State Forest Action Plan.

This Plan is also informed by the steadily-growing national and international movement to ensure healthy soils. As of this writing, healthy soils-related legislation has passed or is pending in 29 US States (Soil Health Institute). Globally, initiatives like 4 per 1000, Regeneration Canada, the Global Peatlands Initiative, and the Global Soil Partnership are building coalitions around enhancing the health and vitality of soils and preventing loss of soil carbon to the atmosphere. Not surprisingly, much of these healthy soils initiatives address agricultural soils. But for states like Massachusetts, and broader regions like New England, focusing solely on agricultural soils would be a missed opportunity. The HSAP is unique in that it considers the opportunities and constraints of five major land covers to support healthy soils that infiltrate, store, and filter water, enhance biodiversity and productivity, sequester and store carbon, and support healthy communities.

Essential Strategies for Soil Health

The Healthy Soils planning process has identified that soil health in Massachusetts relies on the categories of the recommended actions listed below:

- Limit the conversion of Forests, Wetlands, and Farmlands;
- Enhance the functional capacity of soils across all land covers;
- Transform development-related soil management practices;
- Account for Soil Organic Carbon Pools + Sequestration Capacity in all carbon accounting efforts;
- Expand technical, financial, educational, and material support for land managers of all types to employ soil-smart practices;
- Incorporate soil-based criteria into state and municipal legal and financial mechanisms that influence land use and land management practices; and
- Enhance the analytical capacity for measuring and monitoring soil health in Massachusetts.

Soil Organic Carbon: Hidden and Unaccounted Emissions

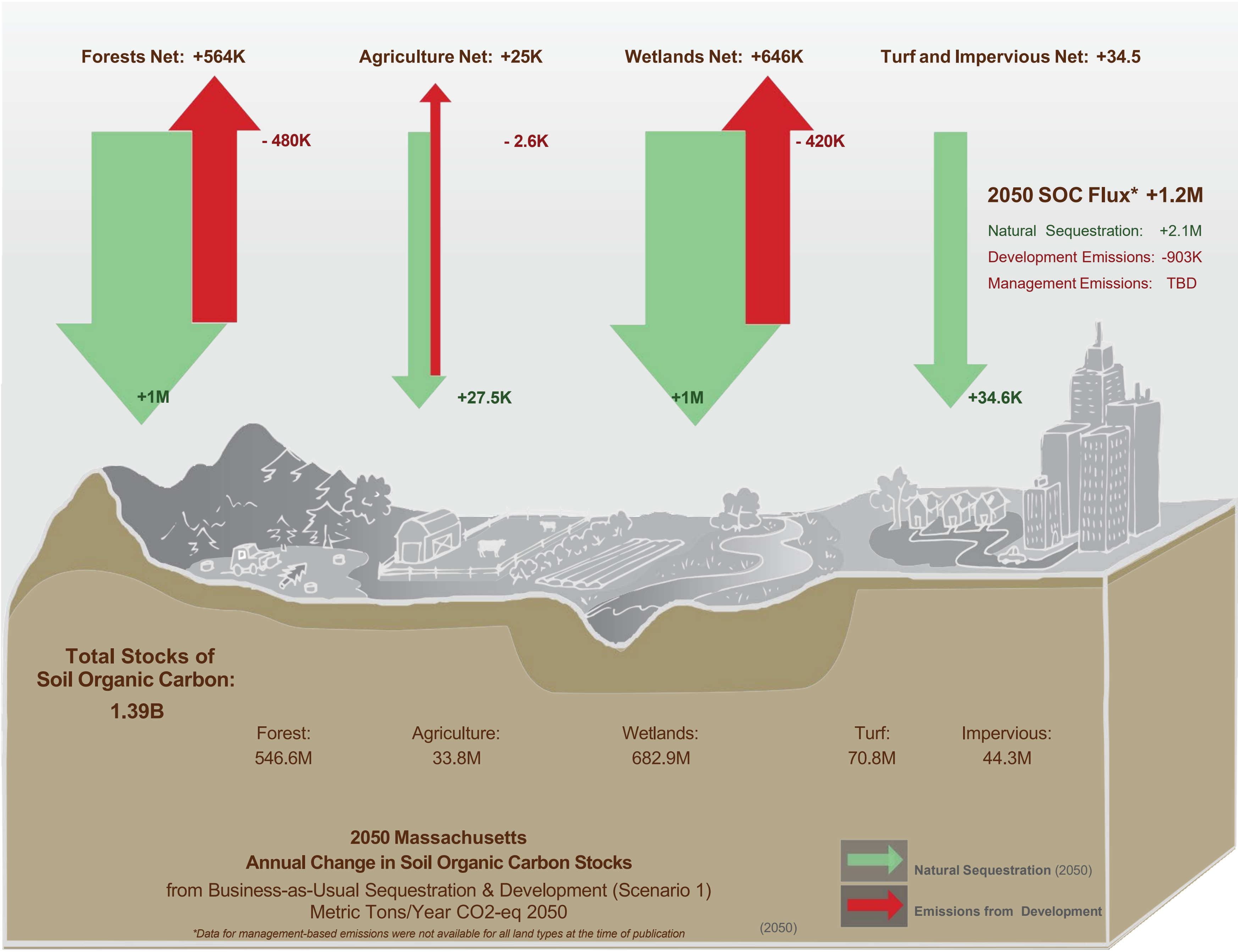
Under the Business as Usual scenario in the Massachusetts Healthy Soils Action Plan, more than 145,000 acres of natural and working lands are projected to be developed between 2020 and 2050. As shown in Figure 1.1 – 2050. Massachusetts Annual Change in Soil Carbon Stocks on page 14, the powerful sequestration capacity of the Commonwealth's forests and wetlands appear to offset SOC losses from this development.

However, Figure 1.1 does not take into consideration the regular losses of SOC from land management, which can be significant. For example, the partial harvest of Massachusetts' forests, roughly 20,000 acres each year, is estimated to release more than 600,000 tons of CO2. This is calculated using data derived from a meta-analysis of SOC impacts of forestry and forest soil carbon stocks. See the Forests section of this report for more information.

Over time, much of this carbon will be recovered as trees regrow, but SOC recovery in the mineral soil may take 15 to 70 years (Hamburg et al 2019, James and Harrison 2016). The adoption of smart soil management practices such as those outlined in the "Massachusetts Forestry- Best Management Practices Manual (Catanzaro 2013) have the potential to reduce SOC losses and should be prioritized.

Protecting and regenerating the carbon stocks of healthy soils will provide many benefits, but improved soil management alone does not have the power to offset the high emissions caused by fossil fuel consumption. Land based solutions must be paired with a transformation of our energy, transportation, natural resource extraction, and consumption patterns.

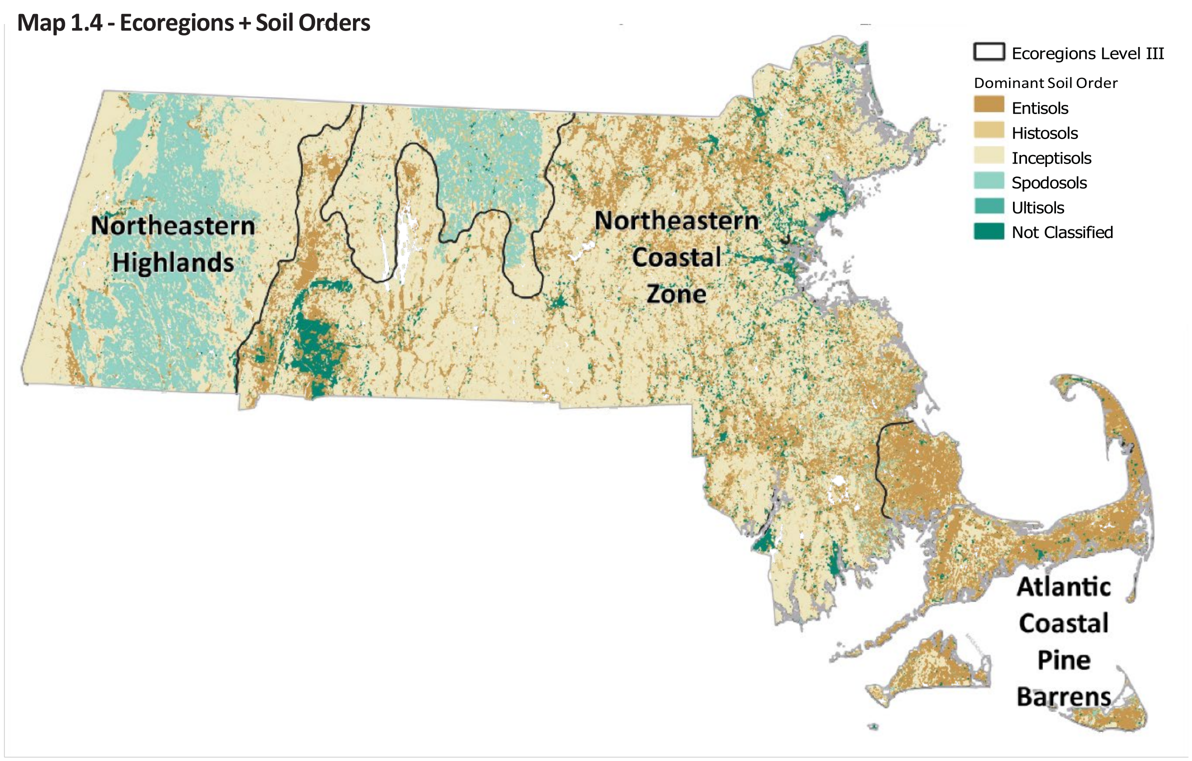
Figure 1.1 – 2050 Massachusetts Annual Change in Soil Carbon Stocks



Soils Across the Commonwealth

The Commonwealth's landscapes are wonderfully diverse. *From the forested mountains of the Taconic and Berkshire ranges in the west, to the mixed farm and forestlands of the Connecticut River Valley and Worcester Plateau; eastward into the densely developed but still resource-rich Northeast Coastal Plain and heavily urbanized Boston Basin, and finally down to the wetland-dominated southeast and iconic coast and islands— for a relatively small state, Massachusetts supports an incredible mosaic of biotic communities and land covers.*

This broad ecoregion patterning helps us to understand the inherent characteristics of soils throughout the State (**Map 1.3: Ecoregions + Soil Orders**). Formed over millennia and informed by geology, climate, time, biota, and topography, inherent soil properties influence the uses particular landscapes can support. Ecoregion patterning is also an essential framework for influencing the dynamic, or use-dependent, characteristics and potential of soil, by encouraging coordinated land management policy.



The Formation of Massachusetts' Soils

By Al Averill, State Soil Scientist, USDA Natural Resources Conservation Service

Massachusetts is within physiographic regions dominated by uplands. The uplands are dissected by river valleys and bordered on the east by coastal lowland. The state is underlain by varied, mostly north-south oriented bedrock types. Each lithology contributes to the characteristics of the mineral fraction of the soils. However, the soils did not form directly from underlying bedrock, rather the material from which the soils developed—parent material—was transported and deposited.

Most of the soil parent materials in Massachusetts are deposits of the last continental glacial ice sheet that covered the region. In the ice were materials scoured and ground from the earth's surface as the glacier encroached including particles of sand, silt, and clay, and rock fragments ranging in size from gravel to boulders. These materials were subsequently deposited by different processes.

Upon glacial retreat, a heterogenous deposit called till remained on the uplands. Of two major till types, lodgment, also called subglacial till, was deposited at the base of glacial ice and is compacted. The characteristic smooth, convex slopes of lodgment till hills facilitate cold air drainage and provide a degree of frost protection. The dense layer underlying soils developed in this material impedes drainage resulting in wetter conditions in the early spring but retains moisture into the growing season. The state's present and historic apple industry is in part, due to the nature of lodgment till soils and landforms. Paxton fine sandy loam, the official state soil, developed in lodgment till.

Conversely, the other major till type, ablation or supraglacial till is relatively loose and permeable having been deposited from suspension as the glacial ice melted. It is common on lower upland side slopes, as a veneer on bedrock-controlled uplands, and in glacial moraines; undulating hills formed at the boundary of glacial ice. Rock fragments in soils developed in till are the building material of remnants of past land use, the stone walls throughout the state's uplands. Soils developed in till are the most extensive in Massachusetts.

Glacial meltwater carried material to lower elevations. The velocity and carrying capacity of the flowing water determined particle size resulting in well sorted layers of sand and/or gravel: the finer silt and clay particles having been carried farther downstream. These glaciofluvial deposits are the source of sand and gravel for excavation operations throughout Massachusetts valleys.

Silt and clay glaciolacustrine sediments were deposited in ponds and lakes formed by glacial scouring and in glacially dammed valleys. These are most extensive in the Connecticut River Valley where glacial Lake Hitchcock stretched from what is now central Connecticut well into New Hampshire and Vermont. Similar glaciomarine deposition occurred in inundated coastal lowlands that were created as the immense weight of the ice sheet caused subsidence of the earth's crust. These deposits were the raw material for the state's past brick making industry.

Post glacially, terraces along major rivers were formed on which fine sand and silt accumulated during flooding events. The soils developed in these alluvial deposits are relatively level and free of rock fragments. They have unrestricted internal drainage. Texture—the relative proportions of sand, silt, and clay—is predominantly very fine sandy loam and silt loam which provides optimal water holding capacity. Due to these characteristics, the soils are well suited for agriculture were not subject to flooding during the growing season. The Connecticut River Valley with its broad alluvial terraces and glaciolacustrine plains is the breadbasket of Massachusetts.

Shallow depressions throughout the State's landscapes where groundwater is at or near the soil surface serve as sinks for organic material. Under these saturated conditions the rate of organic matter accumulation exceeds that of decomposition. Wildlife habitat, flood control, water quality, groundwater recharge, and carbon sequestration are important environmental functions of these highly organic wetland soils.

Soils reflect the characteristics of their parent materials. The bedrock from which the parent material deposition is derived distinguishes and influences color, weatherability, chemistry, and texture as well as rock fragment quantity, size, and shape. The State's soils are typically acidic except for the limestone influenced region around the Housatonic River in Berkshire County. Soils developed in till have predominantly sandy loam and fine sandy loam texture, however local lithology influences variability. Till soils in the Boston Basin are relatively dark in color and have a higher silt content due to the color and weatherability of the area's conglomerate and argillite as compared to soils of the central uplands derived from hard granite and gneiss having lighter color and higher sand content.

Soils formed in glaciofluvial deposits may be dominated by sand, gravel, or both. They are highly permeable and have a relatively low water holding capacity. To some extent, they are distinguished by lithologic origin. The shape of the rounded water-worked gravel and cobbles is further influenced by the composition and structure of the originating rock.

Glaciolacustrine and glaciomarine derived soils have relatively finer texture including clay, silty clay, silty clay loam, and silt loam. These are the only soils in the state that may have a significant clay content. Soils developed from all other parent materials in the state typically have clay content less than 10 percent by weight.

In places, soils formed in till, glaciofluvial, glaciomarine, and glaciolacustrine deposits are influenced by post-glacial, wind deposited fine sand and silt. Consequently, soil surface texture lacks significant variability in these areas.

The state's soils are not highly developed, having formed since the last glaciation, less than about 15,000 years ago. Weathering and biological activity are slowed by seasonal cold and frozen conditions. With few exceptions, layers or horizons distinguished by soil forming processes are weakly expressed.

Generally observable in well drained soils are mineral topsoil that is dark in color due to the influence of organic matter; subsoil weathered to a relatively yellowish or reddish brown color due to iron oxidation; and substratum, the unweathered underlying parent material. Poorly drained soils have higher organic content in the upper part, and subsoil that may be predominantly gray due to a lack of iron oxides. Soils developed in alluvial deposits, the state's youngest soils, may lack a weathered subsoil. Forestland soils typically have a thin, distinct organic surface which is lacking in crop land.

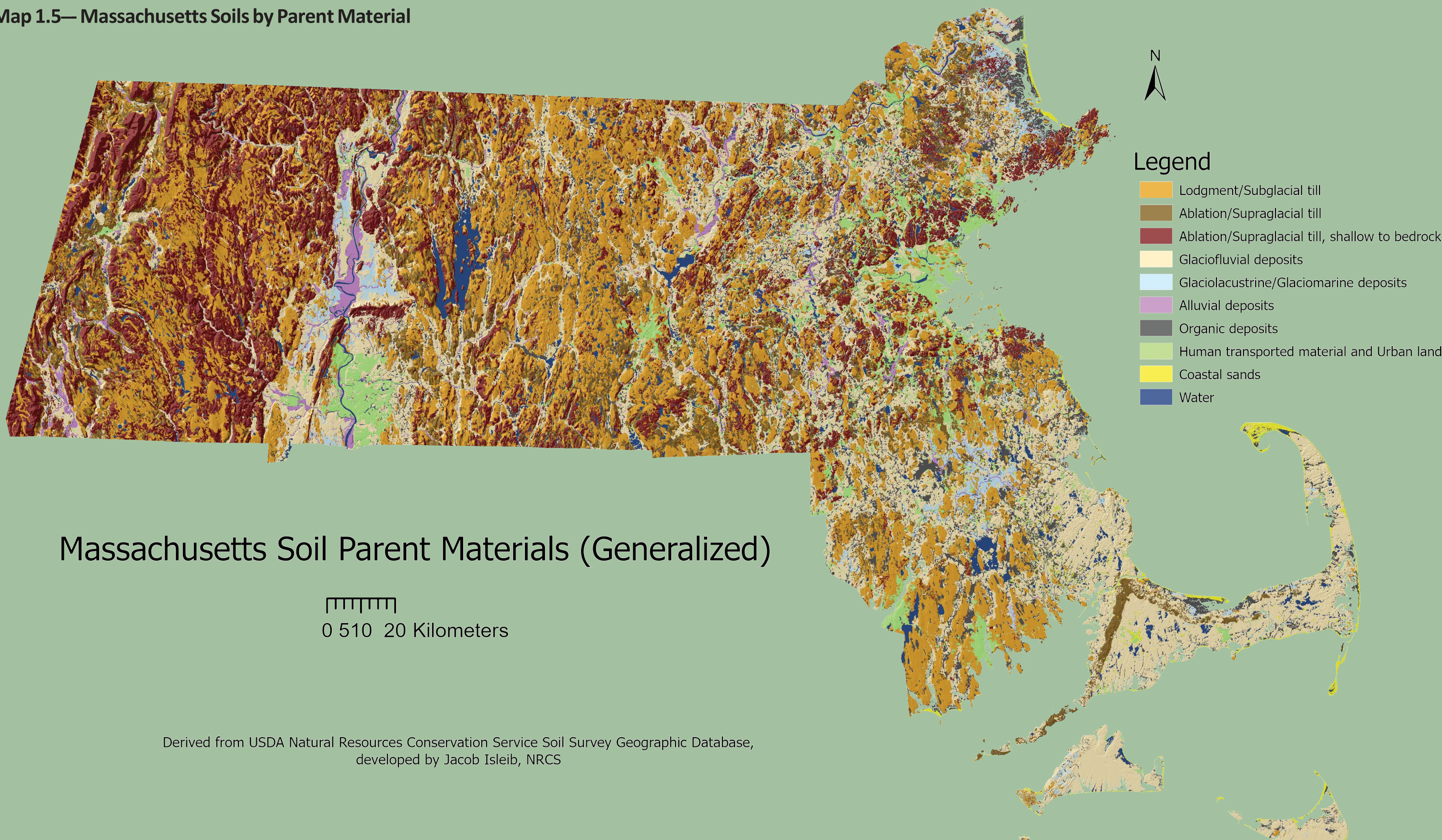
The low clay content in all but soils developed in glaciolacustrine and glaciomarine deposits is attributable in large part to slow weathering over a relatively short period of time. As clays are generally the most chemically active portion of the soil mineral fraction, most chemical activity such as nutrient cycling occurs in the organic component.

In addition to parent material, soil formation, properties, and variabilities are influenced by climate, time, steepness and shape of slope, soil position in the landscape relative to seasonal depth to saturation, and vegetation and other organisms including human activity. The application of these factors enables a degree of predictability that facilitates recognizing and categorizing soil types, their properties, and their location. Applying these principles to the compilation of soils information in a useful format is integral to wise resource planning and management.

The USDA's Natural Resources Conservation Service is tasked with the inventory of the nation's soil resources. This is accomplished through soil survey: the systematic description, classification, and mapping of soils. It applies the principals of soil formation and soil-landform relationships combined with intensive ground truthing. While conducting soil surveys, soil properties are documented and wide-ranging data collected including full laboratory characterization on selected soils.

The soil surveys of Massachusetts recognize about 200 soil types. These are further categorized into soil map units reflecting slope range, surface stoniness, bedrock outcropping, flooding frequency, and landscape composition. Extensive data is provided for each soil map unit, including chemical and physical properties, and interpretations defining the suitability, limitations, and potential for use and management. This information is available for public use and accessible online through the NRCS's Web Soil Survey.

Map 1.5— Massachusetts Soils by Parent Material



Defining, Assessing, and Measuring Soil Health

"Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" –- NRCS

Soil health is defined in the context of its specific land use and environment. It is an assessment of multiple functions and characteristics that can be understood through a set of indicators, or measurable properties of soil (**Table 1.1**). As noted by the NRCS, "useful indicators are easy to measure; measure changes in soil functions; encompass chemical, biological, and physical properties; are accessible to many users and applicable to field conditions; and are sensitive to variations in climate and management" (Soil Health Assessment, NRCS).

Soil health is influenced by a combination of physical, chemical, and biological properties; impacts of land cover; historical use; and historical and present-day management. Successfully assessing and measuring the health of soils—and then adjusting management accordingly—depends on the land type and scale of assessment. Generally speaking, finer scale assessments include direct observation of site dynamics (drainage, vegetative health, soil tilth) and conducting soil tests of physical, chemical, and biological properties. Coarse-scale assessments—like those developed for this report—more commonly rely on proxies like watershed dynamics (including water quality, flashiness & stormwater dynamics), ecosystem productivity and biodiversity, and soil organic carbon.

Table 1.1— Soil Indicators, Functions, + Measures

Indicator Category	Related Soil Function	Some Measures
CHEMICAL	Nutrient Cycling, Water Relations, Buffering	Electrical Conductivity, Soil Reaction (pH)
PHYSICAL	Stability, Water Relations, Habitat	Aggregate Stability, Available Water Capacity, Bulk Density, Macropores, Micropores
BIOLOGICAL	Biodiversity, Nutrient Cycling, Filtering	Microbes, Fungi, Respiration, Soil Enzymes, Total Organic Carbon


Photo Courtesy of MA NRCS

The Benefits of Healthy Soils

Embedded in NRCS's succinct description of healthy soils is a host of soil functions that have co-benefits for ecosystems and human communities. Soil underpins everything—all landscapes and all land uses. Organic matter, that part of soil composed of decaying life, is a key indicator of healthy soils and thus a driver of many positive soil functions—some visible, some not.

Most people understand that soil supports the growth of plants and landscapes that define our daily lives—a grassy lawn, a field of sweet corn, a riverbank, a city shade tree, a protected forest. Of course, soils also support habitat, feed, and forage for the non-human world. Healthy soil makes biodiversity happen. In turn, biodiversity, including all its component parts, from microbes and fungal threads to pollinator plants and mast producing trees, to top predators, is nature's engine that keeps soils healthy and drives carbon, water, nutrient, and energy cycling.

The changing climate has brought into sharp focus another function of soil—carbon sequestration and storage. Second to the world's oceans, soil is the largest store of carbon in the biosphere, holding 80 percent of global carbon. (Lal, 2008). Disturbance of soil through poor land management and unchecked development patterns and practices releases carbon into the atmosphere and disrupt a landscape's ability to sequester carbon through photosynthesis.

Healthy soils are central to retaining, filtering, infiltrating, and storing water. By these functions, soils prevent flooding, erosion, and spreading of contaminants, and they provide local climate cooling. When the characteristic structure, biology and chemistry of soils is intact, they work like a sponge to slow stormwater, recharge groundwater, and clean polluted surface flows. As climate change brings more and heavier storms to our region, these vital soil functions become even more essential.

Healthy Soils = Healthy Waters

Healthy soils have clear benefits to water supply and water quality. However, understanding whether or not a soil is "healthy" is not as simple as checking off a list of binaries. Rather, healthy soils are able to sustain ecosystems thanks to a combination of context-dependent physical, chemical, and biological factors (Cardoso et al., 2013). Despite the overall complexity of soil health, many of its physical indicators are fairly straightforward to identify and have clear implications for hydrological processes such as erosion, aeration, runoff, infiltration rates, and water holding capacity (Schoenholtz et al., 2000).

Soil structure—and characteristics such as porosity, aeration, and water retention—is a physical soil attribute largely influenced by the accumulation of organic matter (Cardoso et al., 2013). Organic matter enables the binding together of silt, sand, and clay particles into secondary units called soil aggregates (Unger and McCalla, 1980). A well-aggregated soil has a mix of small and large pore spaces that enable it to act like a sponge. Pores improve infiltration rates by allowing water to pass into soil at higher speeds during rain events (Groh, 2020), and increase water holding capacity by binding water tightly enough to maintain soil moisture, yet loosely enough to allow for plant uptake (Cates, 2020). In simple terms, the complex structure of healthy soil helps it absorb, retain, and infiltrate water, all of which are important qualities for resilience and ecosystem health.

By improving infiltration, a system will experience a reduction in ponding, runoff, erosion, sediment export to streams, and an increase in water supply to plants; a higher water holding capacity will enable soil to store water during dry periods, increasing resilience to drought and decreasing the risk of stream eutrophication (Bryant, 2015; Cates, 2020).

When soil is compacted, many of these benefits are negated by the elimination of pore spaces. Furthermore, differences in soil structure and surface roughness amplify these impacts depending on land cover type. After a 4-inch rainfall event, for example, the amount of runoff per acre of land is expected to be 13,600 gallons for forested land, 21,700 gallons for turf, 54,300 gallons for an agricultural field with corn or soy, and 105,900 gallons for impervious surfaces (Frankenberger, 2020). While soil can be lost quickly through erosion when soil aggregates are broken down, soil formation is extremely slow. Depending on the system, it can take between 100 and 10,000 years to form an inch of topsoil (Idowu et al., 2019). Supporting practices that build soil organic matter and enable the development of a healthy soil structure is critical for mitigating these system impacts.

Understanding the benefits of soil aggregates helps underscore why soil organic carbon (SOC) is one of the few universally agreed-upon indicators of soil health. For every one percent increase in soil organic matter (which is roughly 57% carbon on a dry-weight basis), soil can hold as much as 20,000 gallons more water per acre (Bryant, 2015). In other terms, a silt loam with four percent soil organic matter has more than twice the water-holding capacity of silt loam with one percent of soil organic matter (Hudson, 1994). This increased water holding capacity means that groundwater recharge can be bolstered, system runoff can be reduced, and the export of sediment and pollutants to waterways can be prevented (Frankenberger, 2020). This also exemplifies how best management practices (BMPs) for growing SOC stocks often do double-duty for protecting water quality, improving resilience to both drought and heavy rain events, protecting critical ecosystem services and vice versa.

The relationship between SOC, soil health, and water quality holds true across land cover types. In areas dominated by impervious land cover, not only does tree planting enhance SOC, but it also has watershed benefits, even when adopted at small scales. In urban and suburban areas, a single deciduous street tree can prevent between 500 and 760 gallons of stormwater per year from becoming runoff; a mature evergreen street tree can intercept more than 4,000 gallons over the same time period (Cotrone, 2015). In agricultural systems, the interconnectedness of SOC and water quality can be seen in the forest buffers typically adopted to filter agricultural runoff. Studies in Maryland have seen nitrate reductions of up to 88 percent when agricultural runoff passes through a forest buffer (Cotrone, 2015). This BMP also has the ability to increase above and belowground carbon sequestration. In wetland restoration, reinstating natural hydrology is a BMP that both builds SOC and improves the self-sufficiency of the ecosystem. Across land cover types, soil carbon, soil health, water quality, and hydrology are inextricably linked.

While soil health and water security are often shelved as two distinct policy areas, it is important to acknowledge the ways in which they are one and the same. In Massachusetts, supporting BMPs that build SOC and promote soil health can have broad benefits for water quality, water availability, agricultural productivity, and ecosystem resilience. Managing for healthy soil is a critical step in preserving water quality and supporting ecosystem services across the state.


Photo Courtesy of MA NRCS

Photo Courtesy of MA NRCS

Spotlight on Soil Organic Carbon

This report addresses the big picture of soil across the Commonwealth, *so the Project Team relied on the proxy of soil organic carbon for understanding the existing conditions and potential for improving soil health throughout the State. Other measurements that indicate soil health and related ecosystem functions and benefits—like productive capacity and biodiversity—are necessary for assessing soil health holistically, and should be applied at the site level.*

Carbon content is one of the few universally agreed-upon indicators of soil health. The natural carbon cycle moves carbon between five great global pools: soils, biomass, oceans, atmosphere, and fossil carbon. About 5% of global carbon is held in soils (the great majority is in the oceans). Various natural and human-driven processes create fluxes, or increases and decreases, in the amount of carbon held in soils.

How does it work? Plants remove atmospheric carbon dioxide and convert it into sugars, fibers, lignins, and other compounds. Within an hour, 10-40% is exuded from the roots to feed beneficial soil microbes. Over time, leaves, roots, and woody biomass decompose. Some of the carbon in root exudates and decomposing biomass returns quickly to the atmosphere, but some is converted into organic matter, including shorter-lived forms as well as long-lived carbon compounds which are bound to clay and silt particles. Organic matter is roughly 57% carbon on a dry-weight basis. The carbon in organic matter is referred to as Soil Organic Carbon (SOC). Every ton of SOC is the equivalent of 3.677 tons of carbon dioxide.

Over time ecosystems like forests, wetlands, and grasslands gradually increase their SOC levels, or stocks, through biosequestration, the annual increase of SOC. Most ecosystems can only sequester carbon until they become saturated, and cannot gain additional new carbon in long-lived forms. Saturation levels vary by ecosystem, climate, and soil—clay and silt soils have higher stocks because there is a greater mineral surface area to bind and lock up carbon than found in sandy soils. Wetlands represent an exception: they continue to sequester carbon indefinitely, because wet soil conditions inhibit aerobic decomposition. This is why SOC stocks in wetlands are so much higher than in other ecosystems. It's important to note, however, that due to historic land clearing and other alterations most land covers in Massachusetts have not reached saturation and opportunities remain to increase carbon storage across all categories of land use described in this report.

Eel River Post Restoration - Photo Courtesy of MA DER

Soil Organic Carbon Stocks in Massachusetts

Figure 1.2 shows average stocks by Massachusetts land cover type, in metric tons per acre.

The Commonwealth's current SOC stocks are estimated at 383 million tons, equal to 1.4 billion tons of carbon dioxide. **Figure 1.3** shows total SOC stocks by land cover type for the Commonwealth. By comparison, annual emissions from all sources in Massachusetts 94.4 million metric tons of CO2 in 1990. Baseline annual natural sequestration in 2050 in the Commonwealth's forests, wetlands, turf, and farmland is estimated at 572,000 tons. This sequestration, equal to 2.1 million ton of carbon dioxide, offsets 2.2% of total 1990 emissions. If this sequestration rate is preserved, or increased, this represents 15% of the additional 14-million tons required to achieve the decarbonization plan.

SOC stocks can also decrease, sometimes dramatically. Natural disasters like fires and droughts can deplete SOC. Climate change is projected to produce profound losses of SOC in some regions, due to extreme weather events, sea level rise, and gradual shift to drier and/or hotter climate in some areas. Human activity can also reduce carbon stocks through degradation of ecosystems, including through development. When an area shifts, for example, from forest to turf, this land cover change results in a loss of SOC stocks. **Figure 1.4** shows projected land cover changes for Massachusetts by 2050.

As such, limiting conversion of forest, wetlands, and agricultural land to other land covers is an important strategy for avoiding land cover change emissions.

Globally land cover change is responsible for 9% of humanity's emissions, the equivalent of some 4.9 billion tons of carbon dioxide per year (IPCC 2019). Projected annual losses for 2050 in Massachusetts are 245 thousand tons of SOC, or 902 thousand tons of carbon dioxide, equal to about 1.2% of the Commonwealth's 2017 emissions.

Figure 1.2— Average SOC Stocks by Land Cover in MA

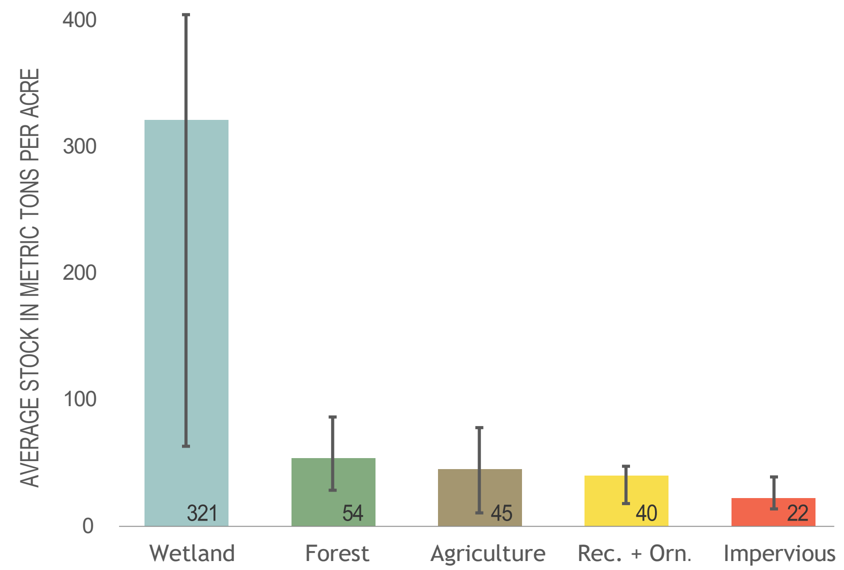


Figure 1.3— Total SOC Stocks by Land Cover in MA

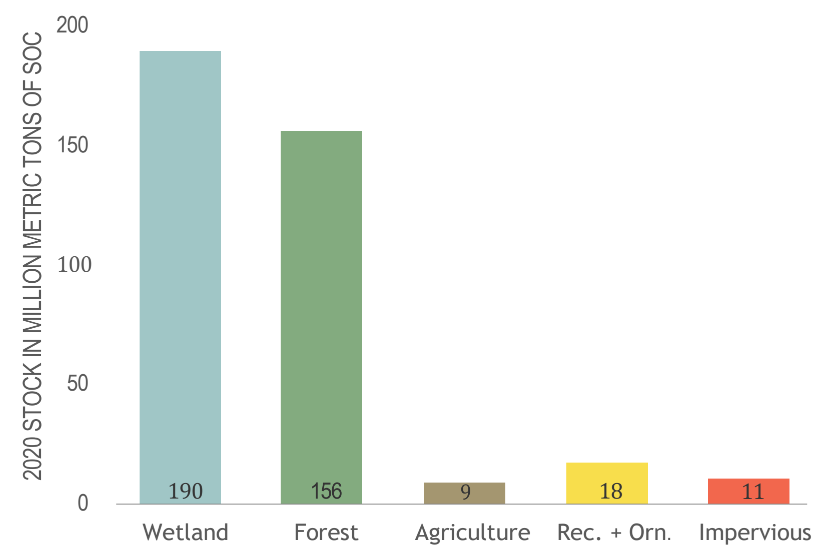


Figure 1.4— Projected MA Land Cover Changes by 2050

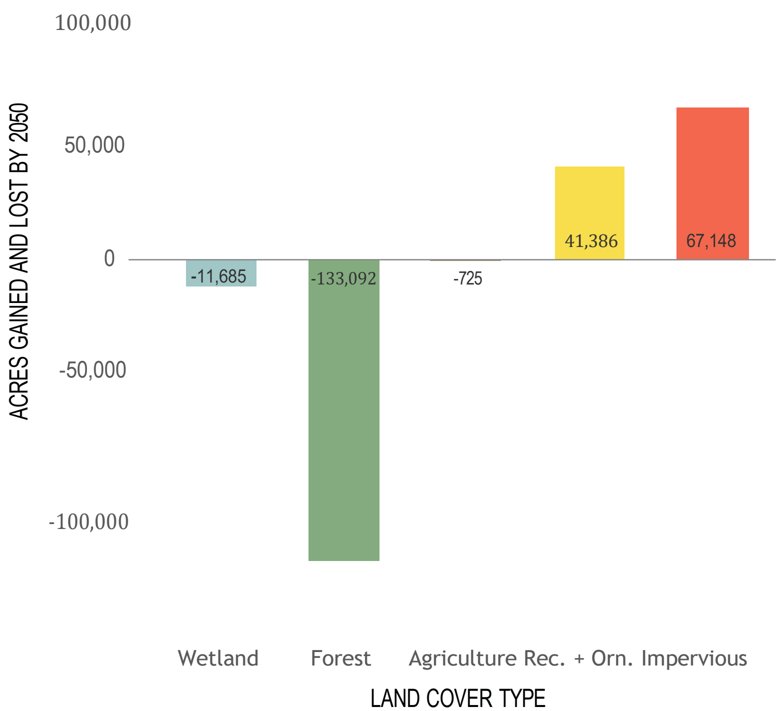
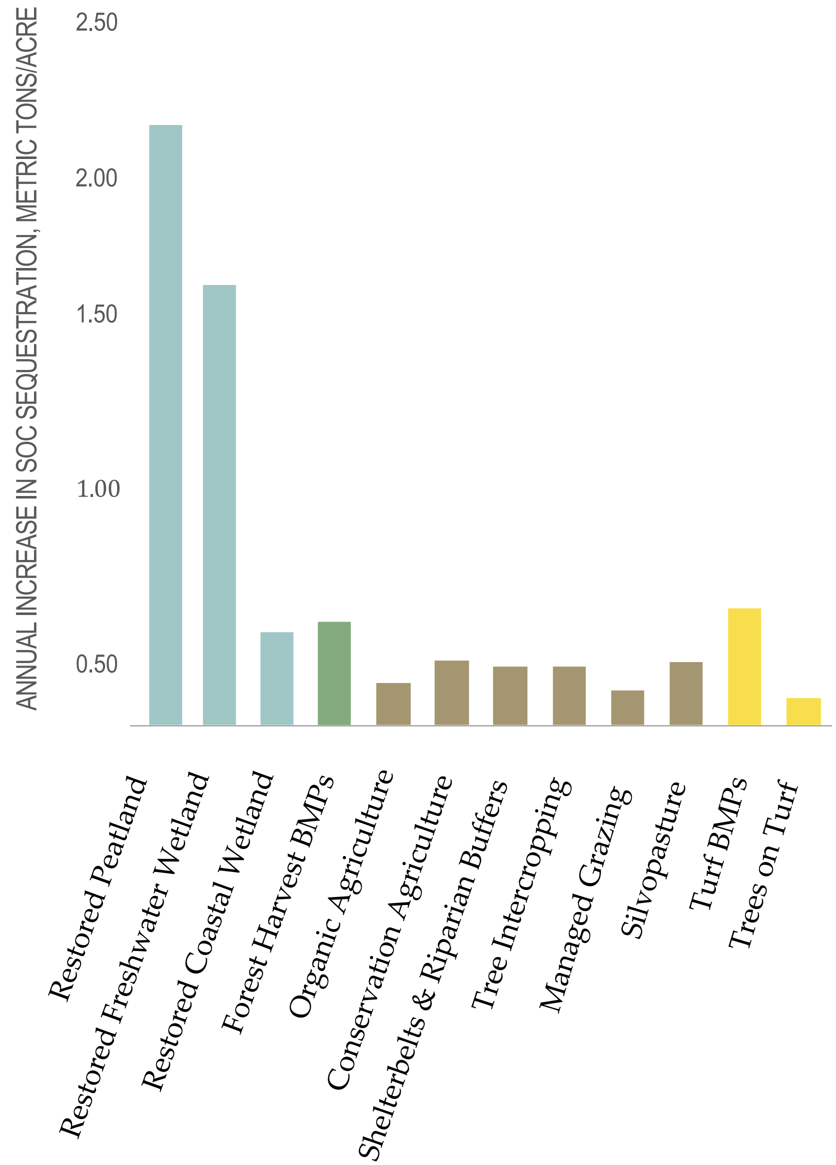


Figure 1.5— Impact of Best Management Practices on SOC Sequestration Rates



Management of existing land use types can also increase SOC. Most of these Best Management Practices (BMPs) were developed not for their climate change mitigation impact, but because they represent good stewardship of natural and working lands. Many improve productivity or ecosystem services like water quality. Globally, adoption of BMPs on forests, grasslands, wetlands, and agricultural land could sequester an SOC equivalent of 14.2 billion tons of carbon dioxide per year (Bossio 2019). Many BMPs also have desirable impacts on carbon sequestration in biomass, which are outside the scope of HSAP's report. Potential SOC gains from Massachusetts BMPs in 2050 are estimated at 18 to 128 thousand tons, equal to 67 to 473 thousand tons of carbon dioxide (equal to 0.3% to 0.8% of 2017 Massachusetts emissions). **Figure 1.5** shows the annual SOC sequestration rates of BMPs used in the HSAP analysis.

Carbon Flux Scenarios

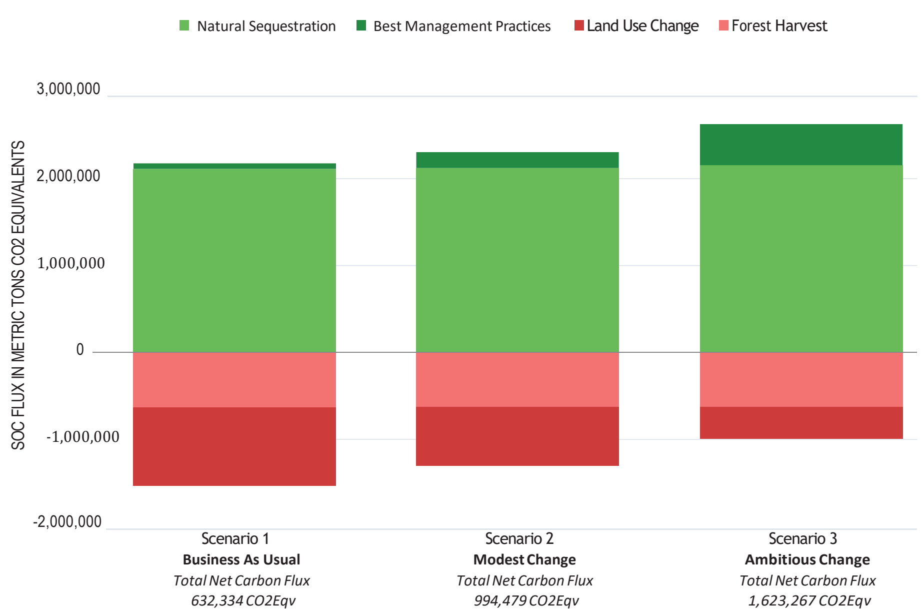
The HSAP developed scenarios to determine the SOC fluxes for Massachusetts in 2050. **Table 1.2** displays a generalized overview; each of the upcoming sections on specific land use types provide additional detail. For BMPs, the first scenario assumes no increase from current adoption, the second assumes modest increases, and the third more ambitious adoption. Growth assumptions are based on historic growth at the state or national level, global projections, and targets set by Massachusetts agencies. For Land Use Change (LUC), the first scenario assumes that all projected development related land conversion occurs, and the second and third scenarios assume that smart growth enables this development to occur while reducing land conversion by 25% and 50% respectively. In all scenarios, the powerful natural SOC sequestration of the Commonwealth's forests contributes the majority of new carbon to the soil.

Massachusetts' soils store an impressive amount of carbon. A top goal of policy efforts should be to safeguard soil carbon from land cover change as much as possible. This is especially true for wetlands, which are disproportionately high in SOC. Adoption of BMPs—particularly those that minimize soil disturbance and accelerate sequestration—is another essential strategy. Massachusetts soils can play a modest, but important role in achieving its goal of net zero emissions by 2050. See the section entitled Maximum Potential of SOC in 2050 on page 26.

Table 1.2— Three Carbon Flux Scenarios

Scenario	BMP Adoption Assumptions	LUC Assumptions
1. Business as Usual	Adoption does not increase from current level	100% of projected development related land conversion occurs
2. Modest Change	Modest increases in adoption	Smart growth achieves development goals, but reduces land conversion by 25%
3. Ambitious Change	Ambitious increases in adoption	Smart growth achieves development goals, but reduces land conversion by 50%

Figure 1.6— Comparison of Annual Soil Carbon Flux in 2050 in Three Scenarios



Maximum Potential of SOC in 2050

Under ideal circumstances, how much could SOC contribute to the net zero emissions budget of Massachusetts? The HSAP team developed a scenario to answer this question, using the following assumptions:

- Zero net new development on forest, wetland, and agricultural land (per smart growth development principles, this means that most new development occurs only on already developed land and remediation occurs on existing development to counter soil carbon lost on new development – on vacant lots, unneeded paved areas, etc.). Full adoption of forest BMPs as in Scenario 3.
- 50% of all turf is planted with trees, and another 25% with turfgrass BMPs.
- 100% adoption of BMPs on agricultural land, including both annual cropland (70% conservation agriculture, 20% organic, 5% riparian buffers and windbreaks, 5% alley cropping) and pasture (75% managed grazing, 25% silvopasture).

Under this scenario, which is technically possible but extremely unlikely, the net flux of SOC at the state level is equivalent to a gain of 2.1 million metric tons of CO2. This represents a modest gain of 526 thousand tons over HSAPs Scenario 3, an increase of roughly a third.

Figure 1.7 - Gain in Net SOC Flux in 2050: Technical Potential

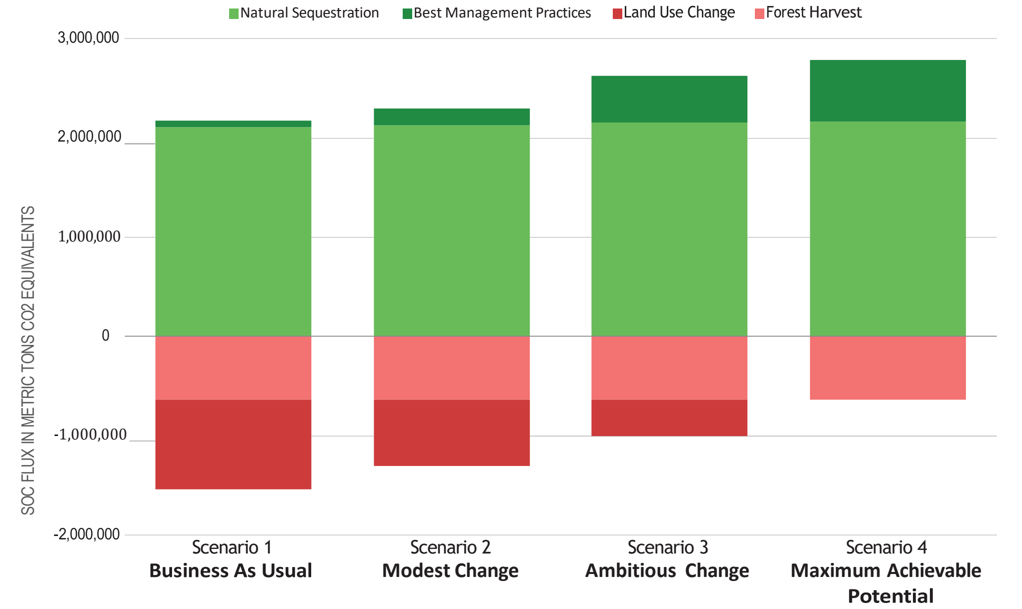
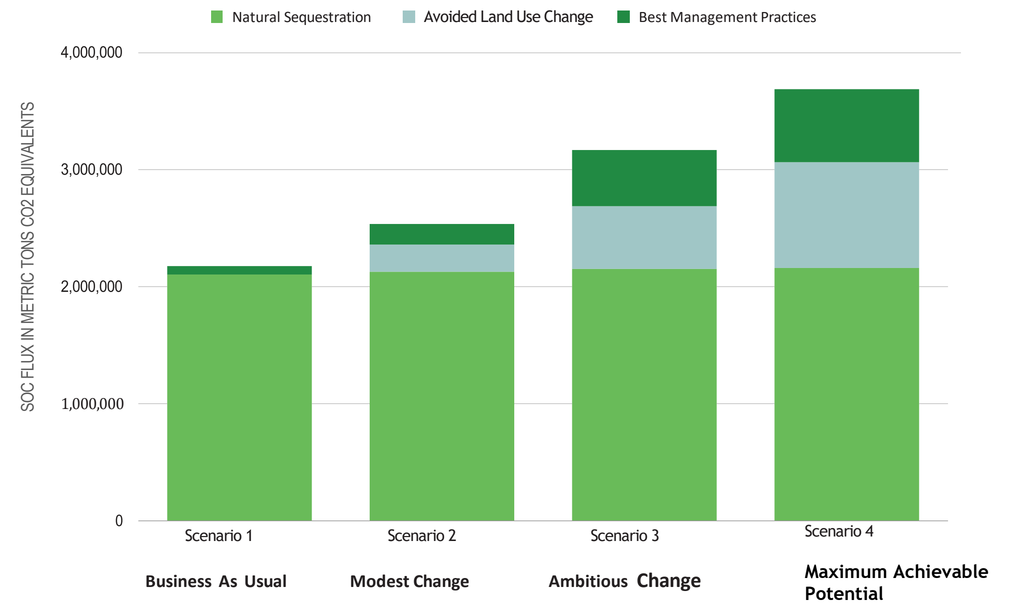


Figure 1.8 - Net SOC Flux Comparison in 2050: Technical Potential



Managing for Healthy Soils: General Principles

The Natural Resources Conservation Service outlines four general management principles that, by protecting soil habitat and feeding soil biota, support soil health. Although developed and primarily applied within the context of agriculture, these principles have relevance for other land covers as well, even if management differs widely. The table below provides a snapshot of how these principles might translate into practice across land covers.

Table 1.3— Land Management Principles for Soil Health by Land Cover

Principles	Forests	Wetlands	Agriculture	Recreational + Ornamental	Impervious
Minimize Disturbance	+ Keep as forests + Minimize fragmentation + Employ BMPs + Restore degraded forests	+ Keep as wetlands + Minimize fragmentation + Restore former/ degraded wetlands	+ Reduce tillage + Establish riparian buffers + Restore degraded farmlands	+ Protect natural resources during development + Employ BMPs + Restore degraded soils	+ Protect natural resources during development + Restore degraded soils
Maximize Soil Cover	+ Leave deadwood and slash in place	+ Vary soil topography in replications and restorations	+ Plant cover crops + Incorporate field residues/mulch	+ Incorporate mulches, compost, and perennials	+ Incorporate green stormwater infrastructure like rain gardens + Remove pavement to restore soil where feasible
Encourage Biodiversity	+ Manage for early and late successional habitats where appropriate + Manage against invasives	+ Manage against invasives + Encourage endemic plant communities in replications/restorations	+ Plant cover crops + Incorporate perennials + Incorporate animals	+ Plant mixed species grasses + Plant pollinator habitat + Plant shrub + tree layers	+ Plant trees, shrubs, grasslands and pollinator habitat
Maximize Living Roots	+ Leave stumps	+ Encourage endemic plant communities + soil function in replications/ restorations	+ Avoid fallow + Cover crops + Strip cropping + Dedicated grasslands	+ BMPs for mowing + Emphasize perennials	+ Plant trees, shrubs, and grasslands and pollinator habitat

Healthy Soils Principles in Practice

Photo Credits from top left: Wachusett Forest Floor, Regenerative Design Group; Tidmarsh wetland restoration, MassDER; Cover crop, MA NRCS; Ornamental and rain garden photos, Regenerative Design Group

Why We Need Soil Restoration, Regeneration, and Stewardship

By Jonathan B. Higgins, CPG, LSP, Principal Earth Scientist, Higgins Environmental Associates, Inc.

Restoration is the directed change toward historic conditions of a system prior to known degradation. Ecosystem and soil restoration is necessary to regain vital ecosystems and ecosystem functions lost over decades and centuries of degradation. Restoration typically refers to broadscale intervention in natural and working lands, but can be applied at any scale.

Regeneration is the directed change toward a system to achieve a high-level of function, resilience, and resistance to degradation. Regeneration may differ from restoration in that historic conditions aren't necessarily the goal. Rather, regeneration strategies are applicable to any land use, and have particular relevance and impact in highly degraded landscapes.

Stewardship is the responsible planning, management, and care of resources, regardless of land use or type. Stewardship should seek to obtain, maintain, and measure restoration and regeneration goals over time. Stewardship by landowners in particular should be promoted and supported at the local, state and Federal level with tax credits, permitting assistance, or allowances.

In order to evaluate soil restoration, regeneration and stewardship opportunities, it is important to understand how "healthy" Massachusetts soil could be given the geology, ecology and climate of our area. The organic soil horizon, or "living" soils in Massachusetts, began following glacial retreat nearly 12,000 years ago. Barren post-glacial mineral soils, consisting primarily of sand, silts, and clays with little to no organic matter, were seeded on the wind and by grazing animals with bacteria, grasses, herbaceous plants, ferns and fungi. Forests beyond the glacial advance would have started to spread into these "new" open land areas.

Based on paleoecology, paleolimnologic evaluation of lake sediment cores, and extensive archaeological evidence, by 10,000 years ago Massachusetts was dominated by pine forests (Shaw, 2020). The climate dried, forest fires were common, and the pine forests were diminished then replaced in dominance by oak forests and open land or an open forest structure that included grasses, ragweed and herbaceous plants (Shaw, 2020, Hall, 2002). These mixed forests, grasses and herbaceous plants were relatively undisturbed until 1650 when European settlers arrived. That's an approximately 10,000 year timeframe for organic, living soils to be developed from microbial and climatic interaction with flora and fauna.

Within a 200 year time period, approximately 75 percent of Massachusetts was deforested and occupied by urbanized areas, pastures and farmlands. Paleolimnological records show that deforestation and agriculture practices led to significant loss of the organic living soil horizon built up over the prior 10,000 years. By 1900, farming in Massachusetts had declined and reforestation began.

In recent times, the health and quality of soils have been negatively impacted. For example, beginning in the mid-1800s, Massachusetts and southern New England were subjected to air-borne wet and dry deposition pollution (aka "acid rain") containing nitrates and sulfates. These acid rains effectively leached minerals such as calcium from remaining organic soils and changed the biogeochemical conditions and nutrient ratios needed for healthy soil processes. Calcium in our soils would otherwise support the health and function of our native plants and trees including sugar maples (Huggett, 2007). Prior to sulfate impacts in particular, these healthy soils would also have been releasing carbon- and iron-rich, organic molecules called dissolved organic matter (DOM) to our natural waters (Likens, 1998, 2002; Monteith, 2007; Ekström, 2011; Schiff, 1990).

Formation of DOM is a natural process occurring today, beyond the historical range of acid rain impacts, that creates red-golden colored water commonly observed in northern New Hampshire and Northern and downeast Maine. DOM and the staining or coloration it adds to natural waters supports native flora and fauna over invasive species and is an important but often unquantified sink for carbon in both our fresh and marine waters and sediments.

Other impacts that affect local soils include the introduction of invasive and exotic species such as earthworms, some insects, and Dutch elm disease. Earthworms quickly break down leaf litter and detritus, reduce soil macrostructure needed for aeration and water retention and allow nutrients and minerals (carbon, nitrogen, calcium and others) to be lost more readily (Bohlen, 2004; Yavit, 2015).

Climate change also has a measurable influence over time on soil health. A warmer climate increases soil temperatures and microbial activity that release soil carbon. Ground freezing, which can increase with less snow cover, can damage fine roots and microbial communities important for soil health (Contosta, 2019). Warming air and soil and increased carbon dioxide content also favors some plants and trees over others such as vines and some invasive species otherwise more acclimated to warmer climates.

References

Bohlen, Patrick J. et al "Influence of Earthworm Invasion on Redistribution and Retention of Soil Carbon and Nitrogen in Northern Temperate Forests", Ecosystems Vol. 7 pp 13-27 (2004) https://doi.org/10.1007/s10021-003-0127-y

Contosta Alexandra R. et al "Northern forest winters have lost cold, snowy conditions that are important for ecosystems and human communities" Ecological Applications Vol. 29, issue 7 (2019), https://doi.org/

Ekström Sara M. et. al., "Effect of Acid Deposition on the Quantity and Quality of Dissolved Organic Matter in Soil-Water" Environmental Science & Technology, Vol. 45. I. 11 pp. 4733-4739, 2011 https://doi.org/10.1021/es104126f

Hall, Brian, et. al., "Three hundred years of forest and land use change in Massachusetts, USA", Journal of Biogeography, (October 2002) DOI: 10.1046/j.1365-2699.2002.00790.x

Huggett Brett A., et al "Long-term calcium addition increases growth release, wound closure, and health of sugar maple (Acer saccharum) trees at the Hubbard Brook Experimental Forest", Canadian Journal of Forestry Research, Vol. 37: pp 1692-1700 (2007) doi: 10.1 139/xO7-042

Shaw, Jonathan, "New England's Forest Primeval", Harvard Magazine, (January 20, 2020) – National Science Foundation funded study, Long-Term Ecological Research (LTER) station–- Harvard Forest, Massachusetts

Likens, G.E., et. al., "The Biogeochemistry of Calcium at Hubbard Brook: Biogeochemistry 41: 89-173, (1998)

Likens, G.E. et. al., The Biogeochemistry of Sulfur at Hubbard Brook", Biogeochemistry, Vol. 60, No. 3 (Sep., 2002), pp. 235-315

Monteith, Donald T., et. al, "Dissolved Organic Carbon Trends Resulting from Changes in Atmospheric Deposition Chemistry", (November 22, 2007) Nature, Vol 450, pp 537-540,

Yavit J.B. et al, "Lumbricid earthworm effects on incorporation of root and leaf litter into aggregates in a forest soil, New York State" Biogeochemistry Vol. 125 pp. 261-273 (2015) https://doi.org/10.1007/s10533-015-0126-z

Guide for Readers

The Planning Process

The process for the Massachusetts Healthy Soils Action Plan started with gathering a 40-member Work Group of state and federal agency and program representatives, and knowledgeable stakeholders. The group held 6 official meetings over the 18 months of plan development, in addition to voluntary participation in over 20 interim planning calls. Work Group members were also called upon to provide specific help in their field of knowledge.

The knowledge and experience of the Work Group members was supplemented by scientific advisors who provided relevant research to support recommendations and areas of inquiry. These advisors were also instrumental in vetting ideas and recommendations for accuracy and efficacy. [See Appendix for a List of Work Group Members and Advisors.]

Listening sessions with specific types of stakeholders (farmers or foresters, for example) and regionally defined stakeholders (like stakeholders in the southeast region of the state) played another important role in bringing more disparate voices and ideas into the planning process. Each one of the 6 listening sessions lasted 90 minutes and included a presentation and discussion. One of the listening sessions took the form of an article and accompanying survey of readers. Most of the listening sessions were in-person meetings on location. A Public Review of key findings and recommendations took place over three webinar sessions.

Land Cover Types

MA HSAP Listening Session Photo: Jim Newman

This report focuses on five land covers: forests, wetlands, agriculture, recreational/ornamental, and impervious/urbanized. Each type has different management goals, stakeholders, soil dynamics, and impacts. To determine the extent and location of the land types, we primarily relied on the 2016 High Resolution Land Cover data set: a 1-meter resolution dataset based on multispectral satellite imagery combined with other data sources and split into 19 classes of land cover. The data set only identifies trees, so we used the USDA Forest Service definition to isolate the forest land cover before clumping these 19 classes into the five land cover categories. Because this is a much higher resolution then the previous 30-meter NLCD data, and produced in a very different manner that the 2005 MA land cover data set, acreages and categories may be different than other reports. When the 2016 data was insufficient or misleading we supplemented it with other data sources including the 2016 USDA-NASS Cropland Data Layer and the 2017 Census of Agriculture data. For more on methodology, see www.regenerativedesigngroup.com/hsap-methods.

Introduction References

Bossio, D. A., S. C. Cook-Patton, P. W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, et al. "The Role of Soil Carbon in Natural Climate Solutions." Nature Sustainability 3, no. 5 (May 2020): 391–98. https://doi.org/10.1038/s41893-020-0491-z.

Bryant, Lara. "Organic Matter Can Improve Your Soil's Water Holding Capacity." NRDC, May 27, 2015. https://www.nrdc.org/experts/lara-bryant/organic-matter-can-improve-your-soils-water-holding-capacity.

Catanzaro, Paul, Jennifer Fish, and David Kittredge. "Massachusetts Forestry: Best Management Practices Manual." MassWoods, 2013.

Cardoso, Elke Jurandy Bran Nogueira, Rafael Leandro Figueiredo Vasconcellos, Daniel Bini, Marina Yumi Horta Miyauchi, Cristiane Alcantara dos Santos, Paulo Roger Lopes Alves, Alessandra Monteiro de Paula, André Shigueyoshi Nakatani, Jamil de Moraes Pereira, and Marco Antonio Nogueira. "Soil Health: Looking for Suitable Indicators. What Should Be Considered to Assess the Effects of Use and Management on Soil Health?" Scientia Agricola 70, no. 4 (2013): 274–89. https://doi.org/10.1590/S0103-90162013000400009.

Cates, Anna. "The Connection between Soil Organic Matter and Soil Water." Minnesota Crop News, March 24, 2020. https://blog-crop-news.extension.umn.edu/2020/03/the-connection-between-soil-organic.html.

Cotrone, Vincent. "The Role of Trees and Forests in Healthy Watersheds." Penn State Extension, August 17, 2015. https://extension.psu.edu/the-role-of-trees-and-forests-in-healthy-watersheds.

Frankenberger, Jane. "Land Use & Water Quality." Accessed July 6, 2020. https://engineering.purdue.edu/SafeWater/watershed/landuse.html.

Groh, Tyler A. "Grounded in Soil: Water Quality Benefits from Healthy Soils." Penn State Extension, May 11, 2020. https://extension.psu.edu/grounded-in-soil-water-quality-benefits-from-healthy-soils.

Hamburg, Steven P., Matthew A. Vadeboncoeur, Chris E. Johnson, and Jonathan Sanderman. "Losses of Mineral Soil Carbon Largely Offset Biomass Accumulation 15 Years after Whole-Tree Harvest in a Northern Hardwood Forest." Biogeochemistry 144, no. 1 (June 1, 2019): 1–14. https://doi.org/10.1007/s10533-019-00568-3. https://masswoods.org/caring-your-land/water

Hudson, Berman D. "Soil Organic Matter and Available Water Capacity." Journal of Soil and Water Conservation, vol. 49, no. 2, Mar. 1994, pp. 189–94, https://www.jswconline.org/content/49/2/189.

Idowu, John, Rajan Ghimire, Flynn Robert, and Amy Ganguli. "NMSU: Soil Health—Importance, Assessment, and Management," December 2019. https://aces.nmsu.edu/pubs/_circulars/CR694B/welcome.html.

IPCC. "2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands — IPCC." Switzerland: IPCC, 2014. https://www.ipcc.ch/publication/2013-supplement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories-wetlands/.

IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

James, Jason; Harrison, Rob. 2016.""The Effect of Harvest on Forest Soil Carbon: A Meta-Analysi"" Forests 7, no. 12: 308. https://doi.org/10.3390/f7120308

Lal, Rattan. "Carbon sequestration." Philosophical Transactions of the Royal Society B 363, 815-830 (2008).

Massachusetts State Hazard Mitigation and Climate Adaptation Plan, 2018

New England Landscape Futures Project, Harvard Forest. https://help.newenglandlandscapes.org/about

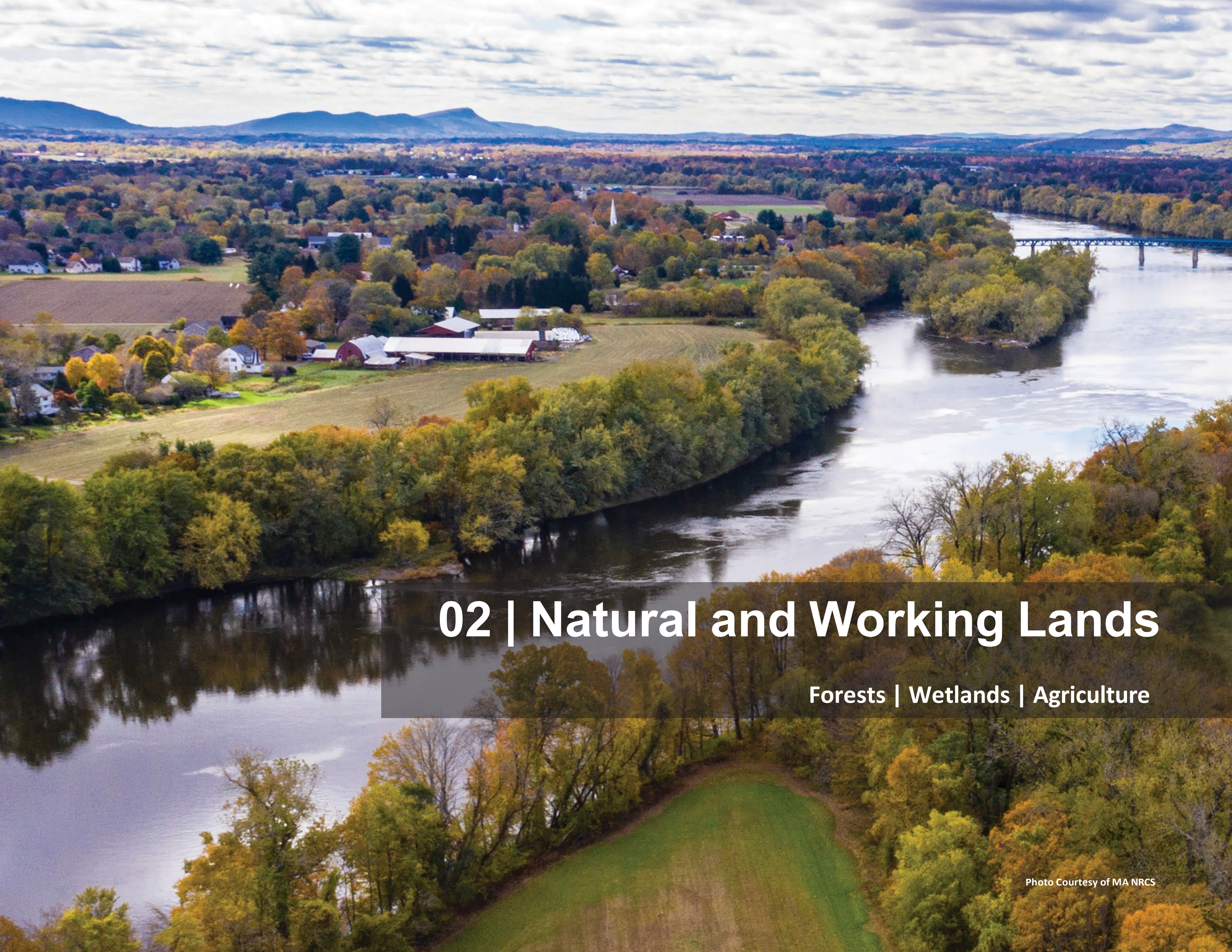
Schoenholtz, S., Helga Van Miegroet, and J. Burger. "A Review of Chemical and Physical Properties as Indicators of Forest Soil Quality: Challenges and Opportunities." Forest Ecology and Management 138, no. 1–3 (January 1, 2000): 335–56. https://doi.org/10.1016/S0378-1127(00)00423-0.

Soil Health Institute Policy Catalog, https://soilhealthinstitute.org/resources/catalog/, Soil Health Institute, Date Accessed, June 26, 2020

Thompson, Laflower, Plisinski, MacLean. Harvard Forest. Land Sector Report, A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study. December 2020.

Unger, P. W., and T. M. McCalla. "Conservation Tillage Systems: Contribution from Agricultural Research, Science and Education Administration, U.S. Department of Agriculture, in Cooperation with the Texas and Nebraska Agricultural Experiment Stations." In Advances in Agronomy, edited by N. C. Brady, 33:1–58. Academic Press, 1980. https://doi.org/10.1016/S0065-2113(08)60163-7.

USDA-NRCS "Principles for High Functioning Soils" Fact Sheet. 2018. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/soils/health/?cid=stelprdb1049236



02 | Natural and Working Lands

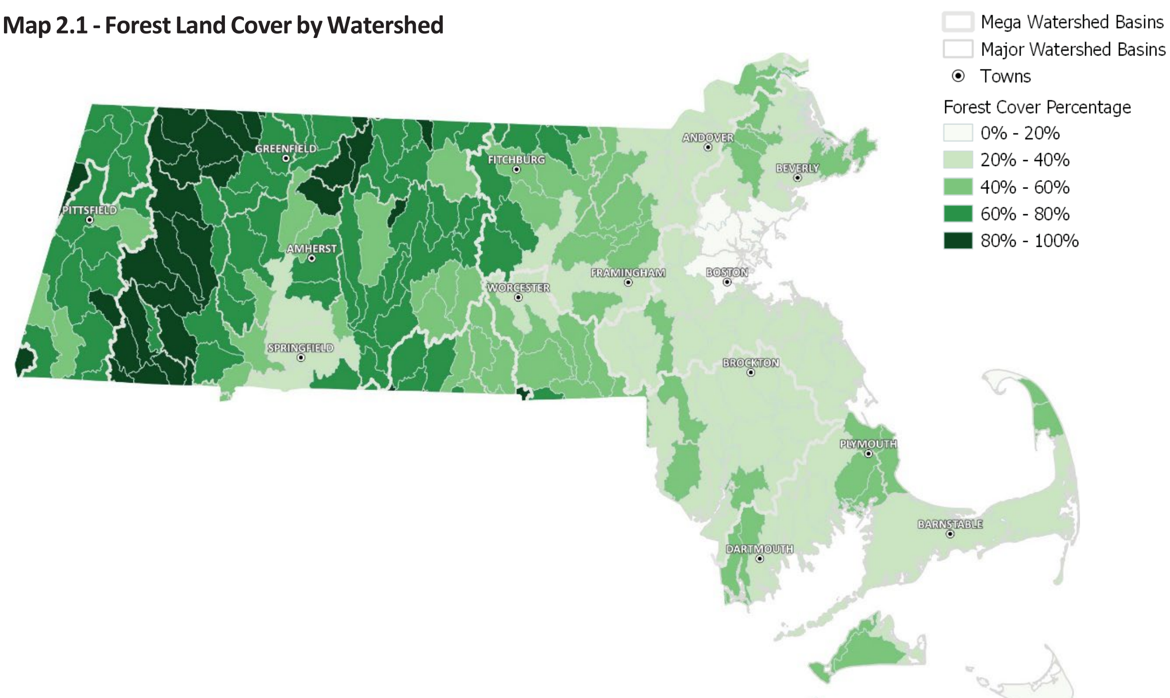
Forests | Wetlands | Agriculture

Photo Courtesy of MA NRCS

Forests

Each year, Massachusetts' forests capture over 1-million tons of carbon dioxide in their soils alone and help to maintain healthy watersheds (Map 2.1) by filtering over 1.6 trillion gallons of water annually (Losing Ground, 2020). *Currently, these 3-million acres of tree-covered soils hold an estimated 156 million tons of soil organic carbon, equal to 574 million tons of carbon dioxide. After wetlands, this is the second largest soil carbon pool in the Commonwealth. Protecting this soil carbon for the long term and increasing the capacity of forests to sequester more carbon each year is an essential for climate change mitigation and habitat preservation.*

Map 2.1 - Forest Land Cover by Watershed

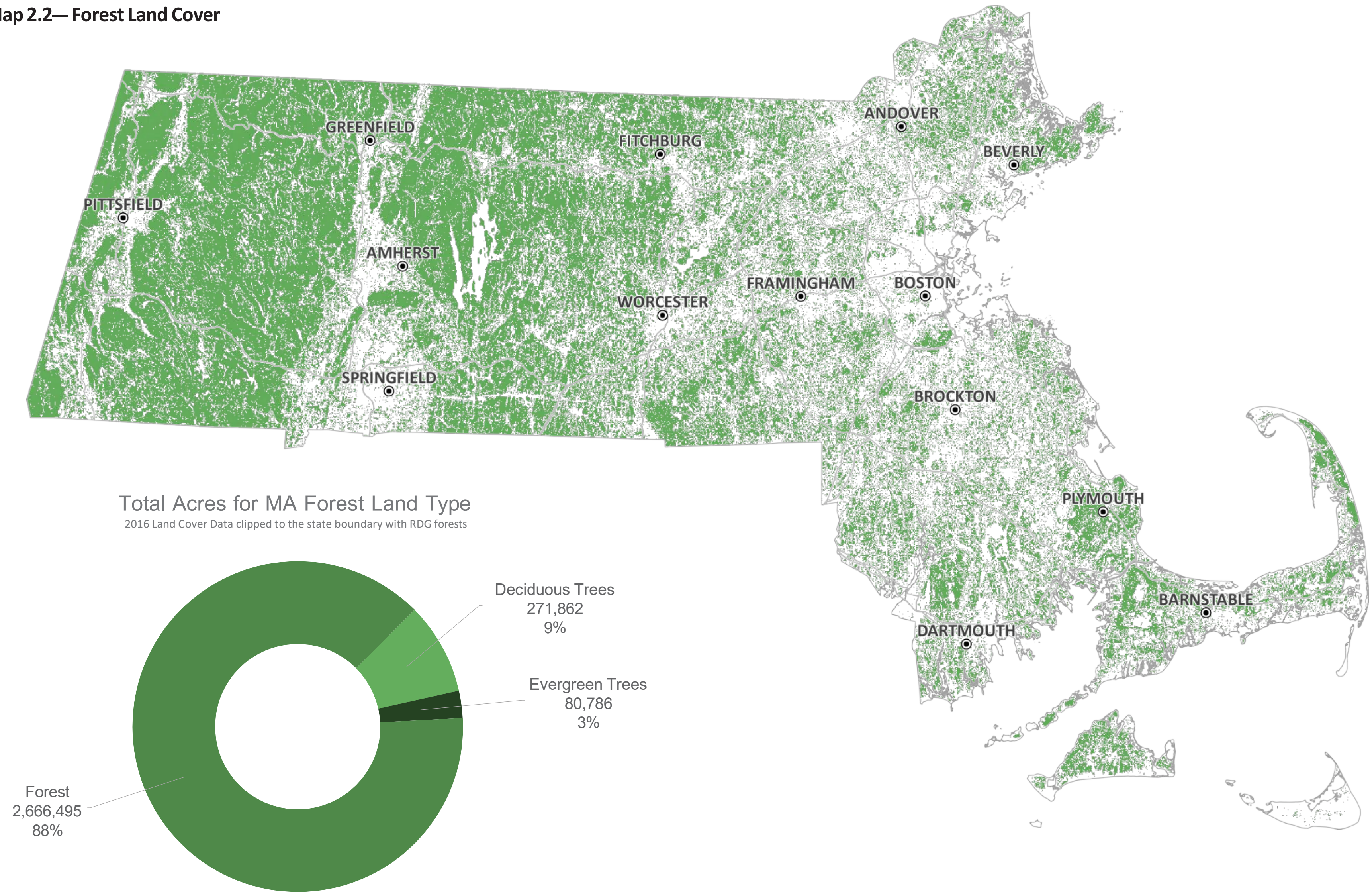


Keeping Massachusetts' forests as forests is the best way to protect the carbon and other critical ecosystem services they provide. Promoting soil-smart forestry and encouraging outdoor recreational opportunities are two ways to incentivize the many owners of Massachusetts' forested soils to remain tree covered.

Patterns and Characteristics

Trees cover more than 3-million acres of land in Massachusetts. Of these, 2,666,495 acres meet the U.S. Forest Service definition of 'Forest' (**Map 2.2)** while 352,648 acres are covered with a variety of different tree covers. In Massachusetts, medium-aged forests (between 65-95 years old) are the most common age class. Oak-dominated central hardwoods and transition hardwoods are the most prevalent forest types in the State (State Forest Action Plan, 2020).

Map 2.2— Forest Land Cover



Defining Forests and Trees

The USDA Forest Service differentiates between forests and non-forest trees based on three factors: tree density, land use, and patch size. These factors are defined briefly in the Forest Atlas of the United States:

> TREE DENSITY refers to the percent of the land covered by trees. Throughout the world the most frequent measure of tree density is percent canopy cover. Forest land use requires that the land either have or be capable of meeting a minimum canopy cover threshold.
>
> LAND USE refers to how people interact with the land and how they intend it to be used. Forest land use requires that no activities are preventing normal tree regeneration and succession.
>
> PATCH SIZE refers to the minimum area required to be classified as a forest. In the United States, the USDA Forest Service defines this as one acre that is at least 120 feet wide.
>
> Using these three factors forest land is defined in the United States as "land that is one acre or greater in size and has at least 10% tree cover, or formerly had such tree cover and is capable of re-growing those trees" (USDA Forest Service, online Atlas)

Of the over 3 million acres of trees identified in the 2016 Land Cover data layer, 2.67 million of these meet the USFS forest land definition for patch size. That means Massachusetts has almost 350,000 acres of tree-covered soils not associated with forests. These trees, typically associated with developed land, show up as remnant woodland in residential neighborhoods, along roadsides, in parks and streetscapes, and interspersed with agricultural lands (2016 Land Cover/Land Use MassGIS Data).

Because of their various distributions, it is challenging to accurately assign the remaining 350,000 acres to the Agriculture, Wetland, or Developed Lands landcover totals found in this report. However, each of those sections speak to the importance of their associated non-forest tree cover and its relationship to healthy soils, with the bulk of the discussion in the developed lands section.

Forest Ownership

In aggregate, the majority of forests and non- forest-trees—nearly two million acres—are privately-owned and unprotected. Half of these private forests are held by "over 26,000 family forest landowners with 10 or more acres" (State Forest Action Plan, 2020, pg.33). The relationship between forestland and farmland is significant, with nineteen percent of private forest landowners operating a farm within a mile of their forest parcel (Resilient Lands Initiative, 2022).

To date, Massachusetts has permanently protected an estimated 1,111,101 acres of tree covered lands. Forty-seven percent of those protected acres are designated as State Forestland, and the remaining are a combination of federal, municipal, Non-Governmental Organizations, and private landholders.

It's clear that small private landowners play a significant role in the long-term protection and good stewardship of the State's forested soils— and several programs run by the Department of Conservation and Recreation (DCR) assist landowners in doing just that. The DCR Working Forest Initiative funded 224 new forest stewardship plans (24,740 acres) in 2018 alone, and more than 2,000 plans on over 200,000 acres since 2009. (Resilient Lands Initiative 2022).

Changes and Vulnerabilities

Land Conversion

Between 2012-2017, over 30,000 acres of MA forests were converted to other land uses (Losing Ground 2020). Scenarios from Harvard Forest's New England Land Futures suggest that nearly 133,000 acres of forest could be developed by 2050. When forests are converted to other land uses, it is not only the above ground forest ecosystem that is lost. Forest soils are irrevocably altered through development and the many ecosystem services a forest provides—particularly related to water quality—are compromised or lost. The cumulative SOC loss from 133,000 acres of forest development emits 14.4-million tons CO_2 to the atmosphere. Conversion of forests compromises adjacent land uses as well. Indeed, the "fragmentation and pollution associated with development and higher road density, among other factors" (State Forest Action Plan, 2020, pg.43) leads to lower ecological integrity overall.

Climate Change + Natural Hazards

The 2020 State Forest Action Plan notes that "climate change is already exacerbating natural hazards and extreme weather events, as well as leading to new impacts that will affect the Commonwealth" (pg. 44). These potential impacts include the reduction in suitable habitat for more northerly species such as spruce-fir forests, which hold more carbon in their soils than do the northern hardwoods (Catanzaro, 2019); altered soil moisture patterns; and increased tree mortality related to insects and disease associated with warmer winters (State Forest Action Plan, 2020). Dr. Kristen DeAngelis, Professor of Microbiology at the University of Massachusetts Amherst, notes that increased winter temperatures can also affect the composition of soil biota and the duration and intensity of their metabolic activities. With greater metabolic activity for longer periods of the year, annual and total soil carbon sequestration can be reduced. Finally, floods brought on by increased frequency and magnitude of precipitation threaten 86,465 acres of forest in 100-year flood zones. Forest management practices that build resilience to the unpredictability of climate change is cited by several current reports as a priority for Massachusetts forests moving forward.

Soil + Land Management

Forested soils are rarely managed directly or intentionally because they're difficult to access. The function and structure of these soils, however, can be strongly influenced by forest management practices. Whether undertaken for commercial tree harvests, wildlife habitat improvements, recreation, or a variety of other purposes, forest management often relies on cutting and removal of some portion of the above ground parts of trees using mechanized equipment. The Massachusetts Forestry Best Management Practices Manual documents a clearly defined set of required and recommended management practices to limit the negative effects and protect soil structure during management. However, some proven practices that reduce the negative soil carbon impact of harvests or increase carbon sequestration and storage, such as afforestation, increasing species and structural diversity, and others documented in the Forest Management for Carbon Sequestration and Climate Adaptation (Ontl et al, 2019) are not included.

Spotlight on Soil Organic Carbon

Globally, 10% of all terrestrial carbon is held in temperate forests, with 60% of that carbon in soils. A study of forest soils of the Northeastern United States calculated that soils store 61% of forest carbon (Lal, 2012). Here in Massachusetts, forests continue accumulating carbon until they are 200 years old or older. The peak period of SOC sequestration (active atmospheric CO2 removal) comes when they are 30-70 years old (Catanzaro et al., 2013).

Harvest of forest products may cause losses of an average of 16% of SOC (Nave 2010, James 2016, Mayer 2020), which is regained over time through ongoing biosequestration. In forests growing on land that was cropland or grazing land in the past, as is the case in many forestlands in Massachusetts, soil carbon recovery lags behind recovery in aboveground biomass. Harvest losses are due in part to the removal of biomass, some of which would otherwise break down and eventually form SOC over time. Harvest impacts on SOC vary and this is an important subject of future research. HSAP assumes that all SOC lost at harvest will be fully recovered in 70 years, as this is a typical harvest rotation length in Massachusetts.

While conversion to development and agriculture causes a loss of forest SOC, the impacts of harvest and other BMPs is more complex and less understood. BMP impacts vary with slope and between soil types. The only BMP relevant to Massachusetts for which strong SOC data is available is thinning. Light thinning increases SOC by freeing up remaining trees for faster growth, while heavy thinning causes SOC losses (Zhang et al., 2018). However, many other BMPs prevent compaction or reduce erosion, both of which are roughly synonymous with preventing SOC losses. Though not model-able due to current lack of quantification, these are included as recommended BMPs based on the advice of the HSAP Advisory Team. Forest BMPs with desirable impacts on water quality can also be assumed to prevent SOC losses (Audrey Barker-Plotkin, Harvard Forest. Personal Communication, 9/2020).

Massachusetts Forest SOC

The Commonwealth has 2.9 million acres of forest and trees. Current SOC stocks are estimated at 156 million tons of SOC, equal to 574 million tons of carbon dioxide. Forest is the largest land use in Massachusetts, and has the largest SOC stock. These figures incorporate data from the NRCS Rapid Carbon Assessment, which show a higher level of forest SOC than commonly used in assessment of New England forests.

In the HSAP analysis, this category includes forest (93%) and some non-grazed grassland and shrubland (7%), of which some is in the process of becoming forest.

Protecting and Enhancing SOC in Forests

Minimizing Soil Disturbance. With best practices, harvest of forest products has the potential for minimal impact on soil carbon (Hamburg et al., 2019). Minimizing soil disturbance in harvest and management—by reducing scarring, limiting rutting depths, harvesting and operating machinery when the ground is frozen, planning for rains and thaws (Catanzaro et al., 2013), locating landing sites near roads rather than in forests (Ontl et al., 2020), and optimizing the number and location of logging roads (Hamburg et al., 2019; Catanzaro et al., 2013)—can help ensure that soil carbon continues to accumulate in forests (Six et al., 2006; Powlson et al., 2014).

Minimizing erosion will become increasingly important as climate change continues to drive more intense weather events in the coming decades (Nave et al., 2019). Note that in some cases soil disturbance is desirable in order to create a seed bed which favors the regeneration of particular tree species adapted to such conditions.

Leave Slash in Place. Slash includes tree tops, branches, and other non-commercial wood that results from harvest. As much slash as possible should be left on site (Hamburg et al., 2019; Catanzaro nd), as studies suggest that forest harvest residue removal can lead to declines in soil carbon of up to 7.5% (Achat et al., 2015). In particular, whole tree removal, which leaves very little material behind to decompose and restore soil carbon, should be discouraged as far as impacts on SOC are concerned.

Ensure Ecosystem Functions are Maintained in Harvest. When harvesting, it is critical that all possible steps are taken to maintain ecosystem functions on site. This includes retaining snags, avoiding grinding up coarse woody debris—and in cases where that is not possible, creating piles that can serve as habitat— (Ontl et al., 2020), harvesting when leaves are off to minimize nutrient removal from the site, and minimizing soil disturbance.

Use Appropriate Equipment. Use of biobased matting for landings (work areas) can lighten the impact of heavy forest equipment on soils. This is especially relevant as the time period with frozen soils is getting shorter, while the trend in the state is towards uses of heavier machinery. Use of equipment with overinflated tires, or tracks instead of wheels, can also reduce impacts on forest soils (Mike Downey, DCR, personal communication, 9/2020).

BMP Adoption Scenarios

HSAP's three scenarios make assumptions about adoption of BMPs and land use change due to development. These are used to calculate the carbon flux from SOC in this land use.

Only the impacts of thinning are modeled in HSAP's forest scenarios (Table 2.1), because this is the only BMP for which quantifiable impacts are available, even though implementation of other forest BMPs is certainly desirable.

Annual Flux of Soil Organic Carbon in 2050

In 2050, the annual net flux of soil organic carbon from forests (**Figure 2.1**) is projected to range from a loss of 20 thousand tons of SOC (73,000 tons of CO2 emissions per year) to a gain of 102,000 tons of SOC (375,000 tons of CO2 sequestration per year). This variation results from differential losses in forest sequestration from land conversion and forest harvest in the three scenarios.

The powerful natural SOC sequestration of forests is tied with wetlands as the largest annual SOC flux in the Commonwealth, at roughly 580,000 tons of SOC or 2.1 million tons of carbon dioxide. SOC losses from harvest average 173,000 tons SOC annually, and projected development losses are 43 to 131 tons of SOC (equal to 160,000 to 480,000tons carbon dioxide respectively). Note that harvest fluxes occur annually and show little change. The harvested area in the state changes little from year to year, and this trend is projected to continue.

HSAP assumes that the number of harvested acres will hold steady at roughly 20,000 acres per year through 2050. The loss of SOC from harvest, based on figures from peer-reviewed meta-analysis, thus holds steady through the period. Note that this lost SOC is assumed to be slowly re-sequestered over a 70-year period.

Forest Soils, Climate Change, and Carbon

By Kristen DeAngelis, PhD. University of Massachusetts Department of Microbiology

Healthy forest soils are akin to healthy soils in any ecosystem, where the qualities that impart health to soils include abundant carbon, with a good balance of other nutrients important for plant growth, lacking in contamination, and replete with living organisms. Soil health is defined by the USDA as "continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." The reason why soil carbon content is valued for healthy soils above most metrics is partly because soils act as a reservoir for atmospheric carbon, a storage place for potential greenhouse gasses. But soils with abundant carbon are also better at holding water and nutrients, making them better for plant growth.

Not all soil carbon is created equally. Soil carbon generally exists in fast cycling pools, which are deposited and lost again in a matter of days to months, and slow cycling pools, which can persist in soils for decades or longer. Until recently, undecomposed plant litter was considered to be the source of slow-cycling soil carbon, but recent advances in soil physical and chemical analysis reveal that almost all persistent soil carbon is processed by microbes before it is immobilized onto mineral surfaces, one of the main mechanisms of persistent soil carbon in mineral soils.

Forest soils are comprised of a surface litter layer, where falling leaves, needles, and woody debris accumulate. Below this litter layer is the organic horizon soil, devoid of minerals but full of fungal hyphae working to decompose the falling litter and transport the nutrients deep into the soil through hyphal networks. The organic horizon soil may also contain some plant roots and germinating seeds. Below the organic horizon is the mineral soil, which may extend for many meters until the bedrock. This organic soil is abundant with bacteria, fungi, and microfauna, with most living within the top 10-15 cm of the organic horizon, and it is here that slow-cycling pools of soil carbon are formed. The association of soil microbes with mineral surfaces, and the eventual death of those same microbes, forms the basis of persistent soil organic matter.

References

Soil carbon is a valuable resource, but all soil carbon is not created equal. https://theconversation.com/soil-carbon-is-a-valuable-resource-but-all-soil-carbon-is-not-created-equal-129175

Cotrufo, M. Francesca, Maria Giovanna Ranalli, Michelle L. Haddix, Johan Six, and Emanuele Lugato. "Soil carbon storage informed by particulate and mineral-associated organic matter." Nature Geoscience 12, no. 12 (2019): 989-994.

Frey, Serita D., Juhwan Lee, Jerry M. Melillo, and Johan Six. "The temperature response of soil microbial efficiency and its feedback to climate." Nature Climate Change 3, no. 4 (2013): 395-398.

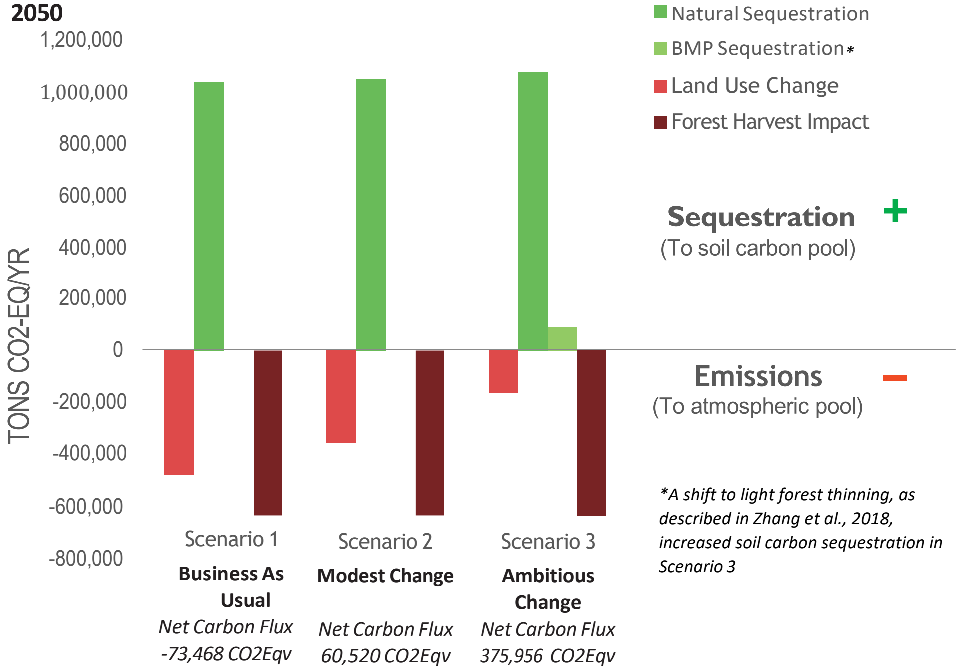
Melillo, Jerry M., Sarah Butler, Jennifer Johnson, Jacqueline Mohan, Paul Steudler, Heidi Lux, Elizabeth Burrows et al. "Soil warming, carbon–nitrogen interactions, and forest carbon budgets." Proceedings of the National Academy of Sciences 108, no. 23 (2011): 9508-9512.

Melillo, Jerry M., Serita D. Frey, Kristen M. DeAngelis, William J. Werner, Michael J. Bernard, Francis P. Bowles, Grace Pold, Melissa A. Knorr, and A. Stuart Grandy. "Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world." Science 358, no. 6359 (2017): 101-105.

Table 2.1 - Forest Scenarios

Scenario	Adoption Assumptions	LUC Assumptions
1. Business as Usual	Adoption does not increase from current level	100% of projected development related land conversion occurs
2. Modest Change	Adoption does not increase from current level	Smart growth achieves development goals, but reduces land conversion by 25%
3. Ambitious Change	Assume shift of High-Intensity harvest (removal of greater than 66% of basal area) to Medium-Intensity (removal of 33-66% of basal area) and Low-Intensity (less than 33% of basal area) harvest based on Decarbonization Roadmap forest estimates; end high-grade harvesting.	Smart growth achieves development goals, but reduces land conversion by 50%

Figure 2.1 - Forest SOC Fluxes in Tons CO2-eq/yr. in 2050



Policies for Protecting and Enhancing Soil Carbon in Forests

1. Shift from High-Intensity to Low- and Medium-Intensity Harvest.

Approximately 8% of acres harvested each year in Massachusetts are high-intensity, characterized by more than 65% of basal area harvested at a time (based on communication with DCR staff, June 29, 2020). Scenarios shifting these acres from high-intensity harvest to medium- and low-intensity harvest (33-65% of basal area and less than 33% of basal area respectively) have the potential to increase SOC storage in harvested forest soils (Zhang et al., 2018). A reduction in acres with high-intensity harvesting should be accompanied by a lengthening of rotation cycles and the elimination of high-grade harvests that remove all high-value trees leaving small trees, and trees of poor quality behind (Catanzaro and D'Amato, n.d.). Massachusetts may consider adopting Whole Tree Harvesting best practices. Many states have required BMPs for whole tree harvesting, for example those developed by the Forest Guild.

2. Expand Afforestation of Former Cropland and Industrial Land.

Afforestation on former cropland has been found to lead to significant increases in soil carbon stocks over 100 years (Mayer et al., 2020) and afforestation of previously mined and industrial land has been shown to increase SOC rates by nearly two-fold over a period of 25-35 years. With over 19,000 acres of active mines and an unknown number of previously mined acres, replanting these soils could have significant carbon, water, and other benefits.

Growing forest crops valuable to farmers like nuts and fruits, short rotation coppice for biomass, or valuable trees for wildlife could add additional benefits to increased SOC gains.

Focusing on vulnerable lands like unforested riparian buffers amplifies these benefits by providing resistance and resilience to flood induced soil erosion. Short-rotation coppice and other dedicated perennial biomass production systems could provide biomass feedstocks with better SOC impacts.

3. Consider Expanding Financial and Technical Assistance Resources for Landowners Participating in Optional Management Practices.

Because harvest rotations are often a generation length or longer, landowners have limited incentives to institute optional forest management practices, particularly ones that deliver SOC gains on long timescales. Financial incentives like annual payments for carbon storage practices and technical assistance programs could help landowners work with foresters and soil scientists to develop forest stewardship plans as well as explore conservation easements.

4. Consider Developing a Grant or Low-Interest Loan Program to Expand Use of Wood-Based Matting for Forest Roads and Landings.

Financing increased use of matting will protect soils from mechanized forestry operations. As matting is a forest product, it provides a market for low-grade wood. Use of matting makes it more possible to work in sensitive sites and seasons while protecting SOC.

5. Additional Research.

Additional examination of the SOC storage potential of best management practices in natural and plantation forests (Bossio et al., 2020), funding for longer-term studies to better understand the SOC recovery rates of harvested stands (Hamburg et al., 2019; conversation with DCR, June 29, 2020), further research on the long-term SOC impacts of biomass harvest for energy production, and increasing the depth of sampling in forested soils (Hamburg et al., 2019) are all recommended. There is also a need for studies that explore the long-term SOC impacts of whole- tree harvesting in MA, particularly the tradeoffs between regeneration, silviculture, and SOC (conversation with DCR, June 29, 2020).

Soil Carbon Emissions and Forestry

The active management of family-owned forest lands helps retain forested acres in Massachusetts. Often guided by professional foresters, these small harvests produce a modest income, supply local forest products, and can improve habitat for wildlife. Threats from climate change suggest that more management will be necessary to preserve the health of forests in coming years.

Despite these benefits, tree cutting releases soil organic carbon through both soil disturbance and the temporary removal of the sequestration capacity of the cut trees. Two global meta-analyses showed a loss of SOC after forestry harvest (Nave 2010 and James and Harrison 2016). Based on these, and a study of northeastern forest harvest SOC losses (Warren and Ashton 2014), HSAP set a rate of 15.8% SOC loss after harvest.

The long-time harvest area of 20,000 ac/yr. is projected to hold steady for the foreseeable future (Mass DCR 2020). Therefore, counting only direct soil carbon emissions, Massachusetts forestry will continue to release 600,000+ metric tons of CO_2 per year-- or 0.7% of 1990 emissions. Though a small percentage of total emissions, this equals 4% of the emission reductions required to meet the 2050 Net Zero goal.

It is important to note that emissions from forestry are different from losses to development or fossil fuel combustion, in that the SOC is re-sequestered as stands regrow after harvest – while SOC lost from development is permanently lost. Based on consultation with our Advisory Team, HSAP set the window for regrowth at 70 years, as this is a typical harvest rotation length in Massachusetts.

Because the period between 2020 and 2050 has been identified by State and world leaders as a critical time for actions to avert the most catastrophic impacts of climate change, understanding the source and scale of all carbon emissions, and adapting activities to minimize releases, even “temporary” sources like forestry harvest, is important.

Soil and carbon-smart best management practices (BMPs) may be one avenue for mitigating emissions from forestry. Many BMPs are already in wide use in Massachusetts, and HSAP has recommended a number of additional BMPs based on our research and in consultation with our Advisory Team.

Many forestry BMPs are known to reduce erosion. Others are shown to increase soil organic matter. However, a lack of research quantifying direct impacts to SOC, makes calculating BMP benefits difficult at present. Currently, light forest thinning is the only BMP shown to increase SOC (Zhang et al., 2018). Future studies may well show reductions in SOC losses from harvest BMPs that are already known to reduce erosion.

Planning Scenarios for the Healthy Soils Action Plan

Due to these research gaps described above, the harvest emissions in all scenarios are shown as being significantly greater than the positive impacts from BMPs.

Scenario 4- Maximum Achievable Potential, shown on page 26, does not offer any increase in forestry BMP adoption or SOC impact over Scenario 3. This is for two reasons; First, many BMPs are already required to be used by all forestry operations in Massachusetts. The Advisory Team reports that adoption of required BMPs is close to 100% today. Hence, these existing BMP benefits are integrated into all scenarios. Second, Scenario Three adds ‘Forest Thinning’ as a BMP with 100% adoption. This leaves no additional forestry BMPs for which SOC impacts have been scientifically quantified to be included in Scenario Four.

As new BMP data become available, SOC retention and sequestration should be revised accordingly.

Recommendations

Keep Forests as Forests. *The forested ecosystems of Massachusetts have among the highest stores of SOC and above-ground-forest carbon in the region-- making soil-smart and carbon-smart forest management essential to comprehensive climate change planning and the preservation of regional water quality and biodiversity. However, these forested soils are extremely vulnerable to development and under increased threat from changes in climate and natural hazards. The majority of forests in Massachusetts are held by private landowners. Though these working landscapes are subject to myriad outside economic forces that challenge the viability of forest-based economies, having the bulk of the forest land under the stewardship of thousands of families who highly value their land results in conservative management and long rotation lengths. Helping these families and other landowners implement better management by involving professional foresters, trained in the latest BMP's and incentive programs will be an important part of developing a flexible and responsive healthy soils programs that prioritize conservation, climate-responsive planning, understanding of the intersections between forests and agriculture.*

Temple Woods, Greenfield MA. Photo: Regenerative Design Group

Land Conversion

F1- Seek to strategically protect healthy forested soils by accelerating conservation of forest parcels.

a. Prioritize municipalities located in the 'sprawl frontier' and other locations with strong pressure to convert forests.

b. Seek to increase funding for forests on prime soils, high-carbon soils, and soils vulnerable to erosion.

c. Encourage adoption of Natural Resource Protection Zoning by breaking down barriers, committing to education and outreach, and providing incentives.

d. Use landcover-related soil health and water quality factors to develop sub-watershed (HUC12) specific forest land cover targets and priorities.

F2- Consider maintaining or increasing incentives that keep forests soils healthy and in forest land cover.

a. Look for ways across existing forest programs to incentivize management practices that enhance soil and ecosystem health.

F3- Direct development toward previously developed and degraded soils.

a. Explore development of incentives and other measures to encourage solar development on already developed lands where co-benefits are high such as parking lots, flat roofs, roadsides, and brownfields.

F4- Expand supports for Smart Growth planning and policies, including both technical and economic supports.

a. Explore implementation of zoning & development strategies that increase density.

F5- Account for forest-based carbon emissions and sequestration in climate change policies and actions.

a. Policy: Account for the sequestration and emission of carbon from forests in state greenhouse gas tracking. Include live below ground biomass and soil organic carbon. Support the forest climate policy recommendations of the Resilient Lands Initiative and their inclusion in the Clean Energy and Climate Plan.

b. Local Bylaw: Encourage no net loss of forests via smart growth concentrated in existing developed areas and tree planting along rivers and in lawn areas as a way to implement the 2020 amendments to the Global Warming Solutions Act for Natural and Working Lands.

F6- Encourage regeneration of forests and tree cover on abandoned and degraded lands.

a. Afforest abandoned agricultural lands, especially with steep slopes or in buffer zones of water resources.

b. Reforest inactive mine lands and gravel quarries.

Soil + Land Management

F7- Increase support for research into the effects of forest management practices on soil health.

a. Long term effects of different management patterns and harvest intensities on soil organic carbon storage and sequestration

b. The extent, intensity, and durability of soil compaction from harvesting and other management

c. Effects of soil decompaction, remineralization, and other fertilization on forest regeneration and composition

F8- Seek to increase funding for professional foresters and other consultants that assist landowners and communities in protecting and managing forests.

F9- Consider expanding BMP incentives that emphasize soil health and carbon-informed management.

a. Incentivize use of matting/timber bridges when soils are not frozen or dry.

Natural Hazards + Climate Change

F10- Increase monitoring + research of ongoing changes to forest soils from climate change

F11- Increase active forest management that favors future climate adapted species.

F12- Support the programs recommended by the Resilient Lands Initiative, including urban greening, park creation, and tree planting in appropriate locations (flood prone, vacant less developable lots, etc.), to increase tree cover in highly impervious and urbanized areas to reduce urban heat islands and improve the carbon and water holding capacity of these heavily impacted soils.

F13- Seek to incentivize strategic reforestation along rivers, streams, wetlands, and other places where forests provide greater resistance and resilience to climate change induced disturbance.

F14- Support the policy recommendation of the Resilient Lands Initiative to plant a minimum of 500 miles of unforested riparian buffers by 2030 using incentives for interested private landowners (including fruit/nut trees along farms and aesthetic landscaping in institutional lawn areas – the two largest areas of unforested river buffers).


Photo: Pixabay Open Source

Forests References

2016 Land Cover/Land Use Data. MassGIS (Bureau of Geographic Information), Commonwealth of Massachusetts EOTSS. Accessed May 2019 from https://docs.digital.mass.gov/dataset/massgis-data-2016-land-coverland-use

Achat, D. L., C. Deleuze, G. Landmann, N. Pousse, J. Ranger, and L. Augusto. "Quantifying Consequences of Removing Harvesting Residues on Forest Soils and Tree Growth – A Meta-Analysis." Forest Ecology and Management 348 (July 15, 2015): 124–41. https://doi.org/10.1016/j.foreco.2015.03.042.

Amacher, Michael C.; Perry, Charles H. 2010. The soil indicator of forest health in the Forest Inventory and Analysis Program. In: Page-Dumroese, Deborah; Neary, Daniel; Trettin, Carl, tech. eds. Scientific background for soil monitoring on National Forests and Rangelands: workshop proceedings; April 29-30, 2008; Denver, CO. Proc. RMRS-P-59. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 83-108.

Bossio, D. A., S. C. Cook-Patton, P. W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, et al. "The Role of Soil Carbon in Natural Climate Solutions." Nature Sustainability 3, no. 5 (May 2020): 391–98. https://doi.org/10.1038/s41893-020-0491-z.

Butler, Brett J. 2018. Forests of Massachusetts, 2017. Resource Update FS-161. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 3 p. https://doi.org/10.2737/FS-RU-161.

Catanzaro P, D'Amato A (nd), Forest Carbon: An Essential Natural Solution for Climate Change.

Catanzaro P, D'Amato A (nd), Increasing Forest Resiliency for an Uncertain Future, Massachusetts Department of Conservation and Recreation Service Forestry Program

Catanzaro, P, D'Amato, A (nd) "High Grade Harvesting: Understand the Impacts, Know Your Options." University of Massachusetts.

Foster, Z., O'Connor, B. 2019. MA Resilient Lands Initiative: Forestry Report. EEA Division of Conservation Services.

Hamburg, Steven P., Matthew A. Vadeboncoeur, Chris E. Johnson, and Jonathan Sanderman. "Losses of Mineral Soil Carbon Largely Offset Biomass Accumulation 15 Years after Whole-Tree Harvest in a Northern Hardwood Forest." Biogeochemistry 144, no. 1 (June 1, 2019): 1–14. https://doi.org/10.1007/s10533-019-00568-3. https://masswoods.org/caring-your-land/water

Institute for Carbon Removal Law and Policy. "Carbon Removal Fact Sheet." 2020 https://www.american.edu/sis/centers/carbon-removal/upload/icrlp_fact_sheet_dacs_2020_update.pdf

James, Jason, and Rob Harrison. "The Effect of Harvest on Forest Soil Carbon: A Meta-Analysis." Forests 7, no. 12 (December 2016): 308. https://doi.org/10.3390/f7120308.

Lal R, Lorenz K (2012) "Carbon sequestration in temperate forests" in Lal, R, Lorenz K (eds) Recarbonization of the Biosphere, Springer, Dordrecht.

Mayer, Mathias, Cindy E. Prescott, Wafa E. A. Abaker, Laurent Augusto, Lauric Cécillon, Gabriel W. D. Ferreira, Jason James, et al. "Tamm Review: Influence of Forest Management Activities on Soil Organic Carbon Stocks: A Knowledge Synthesis." Forest Ecology and Management 466 (June 15, 2020): 118127. https://doi.org/10.1016/j.foreco.2020.118127.

Nave, L. E., K. DeLyser, P. R. Butler-Leopold, E. Sprague, J. Daley, and C. W. Swanston. "Effects of Land Use and Forest Management on Soil Carbon in the Ecoregions of Maryland and Adjacent Eastern United States." Forest Ecology and Management 448 (September 15, 2019): 34–47. https://doi.org/10.1016/j.foreco.2019.05.072.

Ontl, T.A., Swanston, C.W., Janowiak, M.K., Daley, J. Practitioner's menu of adaptation strategies and approaches for forest carbon management. In: Ontl, T.A, Janowiak, M.K., Swanston, C.W., Daley, J., Handler, S.D., Cornett, M., Hagenbuch, S., Handrick, C., McCarthy, L., Patch, N. 2020. Forest management for carbon sequestration and climate adaptation. Journal of Forestry 118(1):86-101. doi:10.1093/jofore/fvz062.

Ontl, Todd A., Maria K. Janowiak, Christopher W. Swanston, Jad Daley, Stephen Handler, Meredith Cornett, Steve Hagenbuch, Cathy Handrick, Liza Mccarthy, and Nancy Patch. "Forest Management for Carbon Sequestration and Climate Adaptation." Journal of Forestry 118, no. 1 (January 7, 2020): 86–101. https://doi.org/10.1093/jofore/fvz062.

Powlson, David S., Clare M. Stirling, M. L. Jat, Bruno G. Gerard, Cheryl A. Palm, Pedro A. Sanchez, and Kenneth G. Cassman. "Limited Potential of No-till Agriculture for Climate Change Mitigation." Nature Climate Change 4, no. 8 (August 2014): 678–83. https://doi.org/10.1038/nclimate2292.

Ricci, E.H., J. Collins, J. Clarke, P. Dolci, and L. de la Parra. 2020. Losing Ground: Nature's Value in a Changing Climate. Massachusetts Audubon Society, Inc., Lincoln, Massachusetts, 33 pp.

Six, J., S. D. Frey, R. K. Thiet, and K. M. Batten. "Bacterial and Fungal Contributions to Carbon Sequestration in Agroecosystems." Soil Science Society of America Journal 70, no. 2 (2006): 555–69. https://doi.org/10.2136/sssaj2004.0347.

The Massachusetts Department of Conservation & Recreation. 2020. State Forest Action Plan.

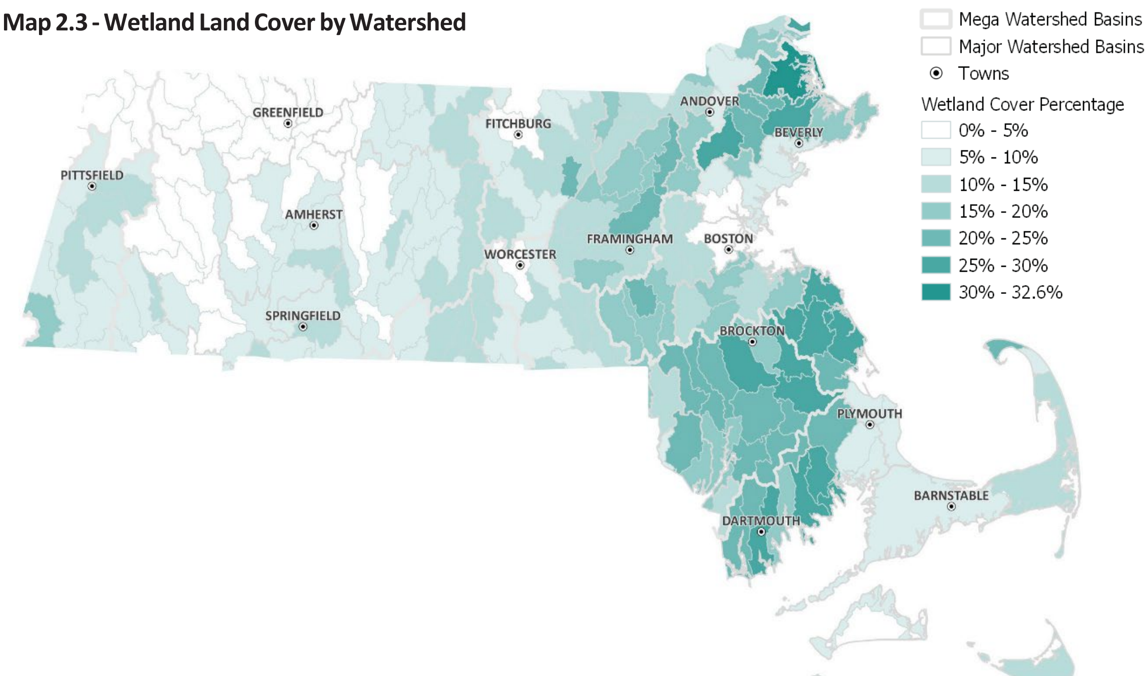
USDA Forest Service Online Atlas. https://forest-atlas.fs.fed.us/grow-forest-extent.html

Zhang, Xinzhong, Dexin Guan, Weibin Li, Di Sun, Changjie Jin, Fenghui Yuan, Anzhi Wang, and Jiabing Wu. "The Effects of Forest Thinning on Soil Carbon Stocks and Dynamics: A Meta-Analysis." Forest Ecology and Management 429 (December 1, 2018): 36–43. https://doi.org/10.1016/j.foreco.2018.06.027.

Wetlands

Wetland land cover, which includes emergent herbaceous, scrub/shrub, and forested wetlands in both palustrine and estuarine environments account for 590,565 acres of land cover in the State. *Wetlands are essential for the State's climate goals—per-acre soil organic carbon stocks of wetlands in Massachusetts are more than twice as high as forests. Wetland function is dependent on a particular set of hydrologic conditions that continue to be threatened by land-use alteration and climate change despite the protections afforded by federal, state, and local laws and regulations. Land management in upland areas surrounding a wetland exert a strong influence on that hydrology. While wetlands themselves may be protected by current laws and regulations, the protection of their upland contribution areas is limited. To maintain healthy wetland soils, we need to maintain healthy upland soils. These are most effectively provided by forested and other natural land cover types.*

Map 2.3 - Wetland Land Cover by Watershed



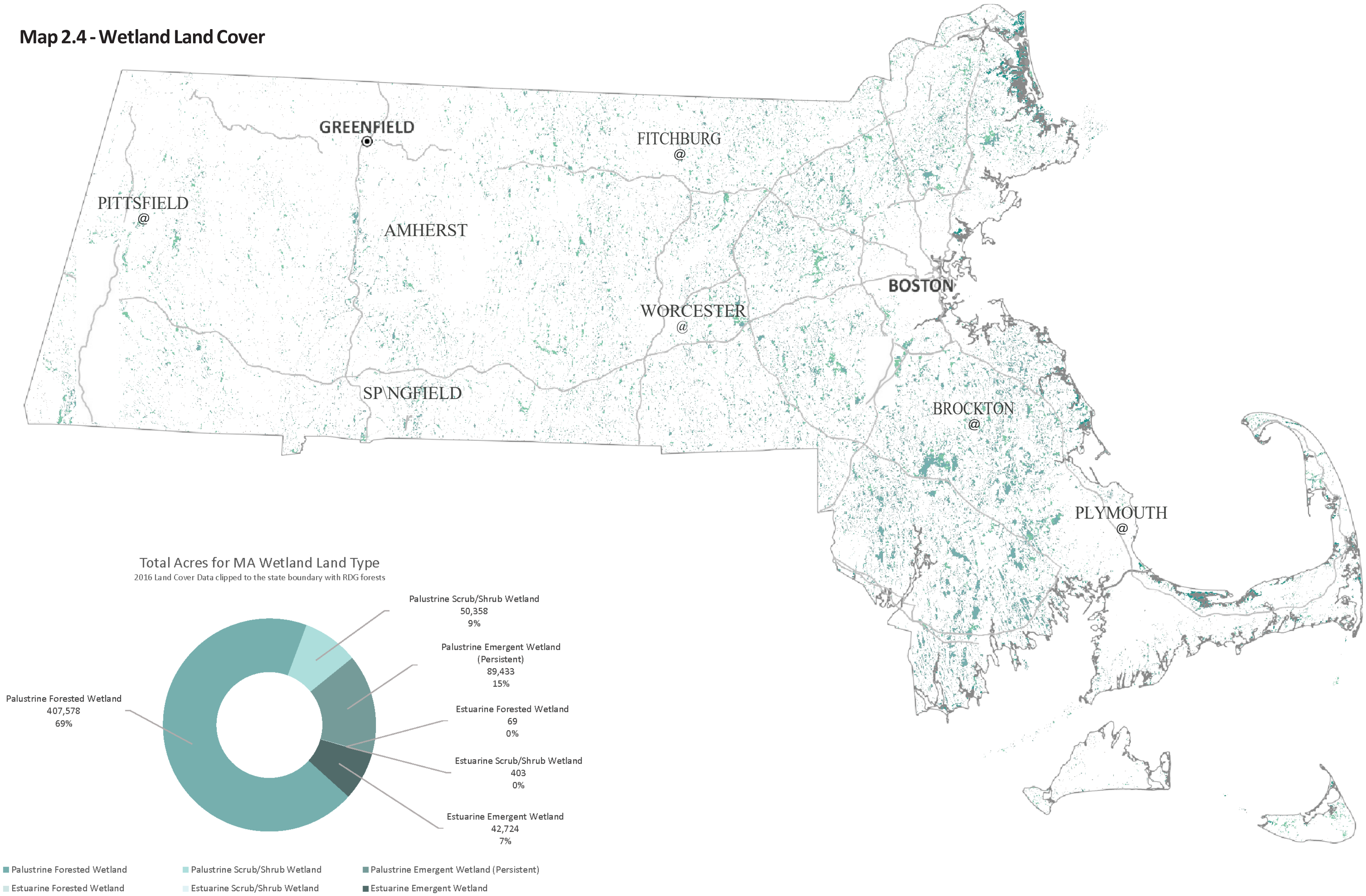
Patterns and Characteristics

Together, tidal and non-tidal wetlands account for approximately 14%, or 590,565 acres, of Massachusetts land cover, with greatest concentrations in the southeast (**Map 2.3)**. The vast majority (93%) of all wetlands are classified as non-tidal, freshwater wetlands (**Map 2.4**). These diverse ecosystems are valued and protected for the many critical functions they perform: safeguarding water supply and quality; providing fish, shellfish, and wildlife habitat, including protected and commercial species; preventing storm damage; flood attenuation; and reducing downstream pollution.

Wetlands form under conditions of extended soil saturation, flooding, or ponding where oxygen is largely removed through microbial processes. This condition results in the formation of visible features that differ from their counterparts on drier land. These features include wetland vegetation that depend on saturated soils fed by wetland hydrology.

These saturated or partially saturated soils create unique chemical and physical conditions that not only provide the important and undervalued ecological services, but the low oxygen environment of wetland soils allow accumulation of extraordinarily high levels

Map 2.4 - Wetland Land Cover



of carbon-rich organic matter. This capacity to accumulate organic matter is especially pronounced in two types of wetlands: peatlands and vegetated coastal wetlands. According to Moomaw et al (2018), "peatlands and vegetated coastal wetlands are among the most carbon rich sinks on the planet, sequestering approximately as much carbon as do global forest ecosystems".

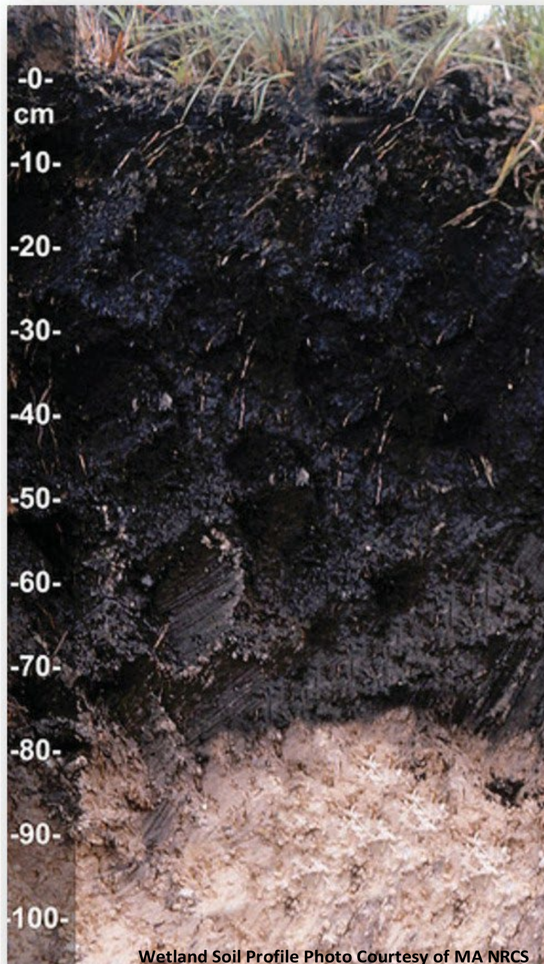
Most wetlands store the bulk of their sequestered carbon in the soil and can continue to sequester carbon indefinitely. Because of these factors, wetlands play a central role in climate change mitigation, both in Massachusetts and globally. Draining or disturbing wetlands oxidizes stored soil organic matter, releasing carbon dioxide and other greenhouse gasses into the atmosphere, and diminishes the capacity of these unique soils to sequester atmospheric carbon.

Freshwater Wetlands

Freshwater wetlands are the most prevalent type of wetlands in Massachusetts, comprising "93% of the acreage of all wetland resources in Massachusetts and include wooded swamps, shrub swamps, shallow and deep marshes, natural bogs, and commercial cranberry bogs" (Rhodes et al, 2019, pg.10). Nearly half of freshwater wetlands are classified as wooded swamps.

Whereas these wetlands all have hydric soils, the soil type may vary from peat to mineral soils, with the drier wetlands more likely to have mineral soils.

Freshwater inland wetlands, in part due to their substantial extent, hold nearly ten-fold more carbon than tidal saltwater sites—indicating their importance in regional carbon storage (Nahlik and Fennessy, 2016).



Wetland Soil Profile Photo Courtesy of MA NRCS

However, freshwater wetlands also emit carbon back into the atmosphere in the form of methane (CH4), which is a greenhouse gas 28 times more powerful than carbon dioxide. Microorganisms present in freshwater hydric soils produce methane in a process called methanogenesis. The rate of methanogenesis may vary depending on factors such as the level of the water table, temperature, and soil substrate composition. Current research continues to explore what factors influence the rates of methane produced in hydric soils. It is clear that disturbing, draining or otherwise altering freshwater wetlands generally leads to increased release of greenhouse gases, and protection of existing natural wetlands is the best means of preventing acceleration of greenhouse gas emissions from wetlands (Moomaw et al 2018).

Research indicates that it can take an extended period of time for the carbon sequestration function of freshwater wetlands to sequester more carbon than is emitted when freshwater wetlands are newly constructed (Neubauer et al, 2014.). Some studies suggest that it may take over 500 years for a constructed wetland to reach negative net greenhouse gas emissions (Anderson et al, 2016). The fluctuations in rates of methane production of freshwater wetlands make it particularly challenging to quantify net greenhouse gas reductions of constructed or replicated wetlands within the constraints of carbon offset and trading programs. The difficulty in replacing the carbon sequestration function of wetland soils highlights the importance of avoiding impacts to existing wetland soils and limiting the construction of new wetlands.

While the historic levels of atmospheric carbon dioxide elevate the attention placed on wetland carbon dynamics, it is important to note that new wetlands do provide many ecosystem benefits to a watershed, and their creation, through human intervention or natural processes should be evaluated holistically. Water quality improvements, stormwater retention, and ground water recharge are among the services that most directly benefit human communities.

Saltwater Wetlands

Coastal wetland resources, including salt marshes, tidal flats, beaches, dunes, barrier beaches, rocky intertidal shore, and coastal banks, make up 7% of wetland resources in Massachusetts (MassDEP, 2019). Coastal wetland resources provide ecosystem services in the form of protection from storm surges and erosion, among others. Studies have estimated the value of storm protection that U.S. marine saltwater wetlands provide at $23.2 billion a year, or an average of over $3,000 per acre per year (Moomaw, 2018).

Saltwater wetlands including salt marshes have lower methane emissions than freshwater wetlands because the abundant sulfate ions in seawater limit microbial methane production. For this reason, some scientists argue that replicating and restoring salt marshes is more effective at sequestering carbon and reducing overall greenhouse gas emissions on relevant time scales than replicating or restoring freshwater wetlands (Kroeger et al, 2017).

Photo Courtesy of CZM, Flickr

Vulnerabilities

Development

Residential and commercial development is a primary source of wetland loss (estimated at 1,192 acres of wetlands lost between 1990 and 2012), which is followed by conversion to cranberry bogs (MassDEP, 2019).

Per the Wetlands Protection Act (WPA) Regulations, projects that impact up to 5,000 square feet of wetland must be mitigated with 1:1 wetland replication of altered surface area. However, the regulations do not require replication of the specific soil type or soil depth that has been altered. In addition, while replication does include hydrology and vegetation performance standards, there are no soils-related performance standards such as soil function or soil characteristics. This is significant, for example, because the impact on the carbon cycle differs significantly if three inches of an A horizon (the A horizon is the surface "topsoil" layer) in a wetland mineral soil is disturbed versus three feet of peat in a bog. An alteration of a 3-inch A horizon mineral soil will result in significantly less carbon loss than alteration of a 3-foot layer of peat. Under WPA regulations, monitoring of replicated wetlands relies on assessment of vegetation, rather than a fuller assessment of wetland function that includes soil structure and function.

A 2018 review of replicated wetlands in MA showed that only 35% of replicated wetlands were built and successfully met all of the required performance standards, and that 14% of required replications were never constructed at all (Rhodes, 2018). While increased enforcement of the existing regulations could improve these outcomes, it would be of benefit to explore implementation of more specific performance standards for soil function, in order to increase the rate of wetland soil regeneration and carbon sequestration as well as overall wetland function, given that healthy soils are a proxy for a healthy ecosystem.

The most commonly cited reason for the failure of wetland replications is lack of education and training for the entities responsible for constructing the wetland replications. In addition, soil compaction is common during construction and a lack of microtopography in the grading leads to sites with monotypic vegetation. Further, elevation is often used to determine location rather than groundwater levels. Finally, there is sometimes a mismatch of expertise between ecological professionals and construction contractors that results in implementation challenges.

Soil + Land Management: Agriculture

Humans have been cultivating crops in wetlands and draining wetlands to aid in the cultivation of crops for thousands of years. The Wetlands Protection Act permits the continuation of agricultural activities that began before 1996 and that are located in wetlands and regulates the conversion of wetlands into new agricultural land.

Drainage tile, which refers to any system of underground drainage, is often used to drain wetland soils for agricultural cultivation. The installation of drainage tiles was a technology widely implemented during the western expansion of the US beginning in the early 19th century, and continues to be practiced today. Drainage ditches are also used extensively throughout Massachusetts to make wetter areas arable. These areas can be restored as wetlands through breaking or removing sections of drainage tile or reconfiguring ditches and adding ditch plugs. Because many of these areas contain hydric soils, restoring formerly drained wetlands often is less costly and more effective than constructing wetland replications in upland areas. Additionally, restored freshwater wetlands often sequester net carbon faster than wetlands constructed in uplands.

Cranberry Production. Cranberries are a wetland plant that has been cultivated extensively in Massachusetts since the 1800's. Wetlands, specifically bogs/peatlands, were utilized for cranberry cultivation due to their acidity and abundant organic matter and water, resulting in thousands of acres of alteration. Management of cranberry bogs includes regular additions of layers of sand over the native soil surface, which helps stimulate root and shoot growth and suppress weeds and disease. Cranberry bogs are bordered and connected by a series of constructed ditches, which, along with dikes and other structures, allow for irrigation and flooding. Seasonal flooding of the bog provides protection from winterkill, and in some cases, is used for harvesting.

Management practices associated with cranberry farming have several effects on wetlands. The two most profound practices are 1) sanding, which creates a 1-3 foot (or more) mineral surface layer over the native peat, and 2) ditching and water control structures, which can quickly drain water from the bog surface when it isn't required. These practices often result in a disconnection between the water table and bog surface and can persist after abandonment, potentially altering the successional trajectory of a bog, even to the point where it might not meet the definition of a wetland.

Cranberry bog creation was the second largest human cause of loss of natural freshwater wetlands between 1995 and 2005. Not all of the alterations that occurred were permitted, and since the Wetlands Change Project done by MassDEP (using remote sensing data) highlighted the extent of unpermitted conversions, the cranberry industry has taken proactive steps to work with MassDEP in helping to reduce these occurrences. Subsequently, natural freshwater wetland alteration from cranberry bog activity had a noticeable drop in occurrences between 2006 and 2012, and the majority of new cranberry bog creation has occurred on upland soils.

Cranberry production in Massachusetts is currently in decline. This is a result of warmer temperatures, combined with market forces and increased competition from other areas with higher yielding varieties. In addition, other states' cranberry regions have lower overhead costs per acre due to their larger bog sizes, thus reducing the comparable profitability of the Massachusetts industry.


Photo Courtesy of MA NRCS

Massachusetts Division of Ecological Restoration (DER) established a program to incentivize the restoration and long-term conservation of former cranberry bogs. The "Cranberry Bog Program" aims to return these bogs to high-quality, self-sustaining wetlands, and in doing so, restore critical wetland functions such as water filtering and carbon sequestration.

Other Management

Little is documented about the extent or impact of non-agricultural and non-restoration management activities within wetland areas in Massachusetts, such as treatment with herbicides to reduce populations of phragmites and purple loosestrife or use of larvicide and drainage canals to control mosquitos. While certain interests may be served by these management activities, additional study is recommended to understand the impact these and other management practices have on the function and health of wetland soils.

Climate Change + Natural Hazards

Moomaw et al (2018) state, "Wetlands sequester some of the largest stores of carbon on the planet, but when disturbed, drained, burned or warmed, they release the three major heat-trapping greenhouse gases (GHGs), carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O)." Many of the effects of climate change have the potential to speed this process, creating a positive feedback loop between the effects of increased greenhouse gasses in the atmosphere and the further increase of those greenhouse gasses.

Temperature Increase. Rising temperatures and an increase in frequency of drought conditions are causing warming wetlands to release carbon.

Sea Level Rise. Sea level rise poses different types of threats to coastal wetland resources and freshwater resources. On the coast, sea level rise may 'pinch' existing salt marshes and tidal marshes between the high-tide line and infrastructure or naturally occurring steeply graded topography, resulting in an overall reduction of coastal wetlands. This is sometimes referred to as "coastal squeeze" (Torio and Chmura, 2013). To combat this, in some coastal areas, actions are being taken to conserve areas where salt marshes might migrate as sea levels rise. Protecting these potential migration corridors is a recommended action for climate mitigation and resilience.

The intrusion of saltwater further upstream into rivers and inlets threatens to change the vegetative makeup of inland wetlands, as well as contaminate groundwater and aquifers. There is the possibility that "freshwater remediation can reduce salinity and revive freshwater forests stressed by salinity intrusion" (Moomaw et al 2018), however, to date there has been no long-term monitoring showing the survival rate of vegetation following remediation (Moomaw 2018).

Spotlight on Soil Organic Carbon

While wetlands make up a smaller proportion of global land mass than forests or grasslands, they hold the highest carbon stocks and deliver the greatest hydrologic ecosystem services per unit area, making them critical tools for climate resilience (Zomer et al., 2016) and for climate mitigation (Nahlik and Fennessy. 2016, Moomaw et al., 2018). Wetlands contain 20% - 30% of global soil carbon on only 5% - 8% of the land area (Nahlik and Fennessy, 2016).

Unlike upland soils, where carbon sequestration is limited by the quantity of available mineral particles, wetlands can continue to sequester carbon for thousands of years, because soil conditions are anoxic for extended periods of time (Paustian, 2014). In the northern United States, most peatland soils contain an organic matter layer that is 1-3 meters deep, with initial deposits occurring between 6,000 to 11,000 years ago (Nave et al., 2017).

However, wetlands have been degraded—or lost altogether—at high rates. Between 1780 and 1980, the U.S. lost 104 million acres of wetlands—equivalent to 53% of the total wetland acreage (Dahl, 1990). Some studies estimate that globally, wetlands have declined by 64 to 71% in the 20th century alone (Davidson, 2014). When wetlands are drained or soil is degraded, stored carbon stocks can reoxidize, which leads to rapid soil carbon loss. In this instance, SOC pools built up throughout the course of centuries and millennia can be released as greenhouse gas emissions in just a few decades. These rates of emissions are currently equivalent to 6% of total anthropogenic emissions (Joosten et al. 2016). Given the high stocks of soil organic carbon (SOC) in natural wetlands as compared to restored or created wetlands (Nave et al., 2019), the large emissions impacts of wetland soil reoxidation, and the low cost of wetland conservation relative to restoration (Bayraktarov et al., 2016), it is critical that wetlands in Massachusetts are conserved.

Massachusetts Wetland SOC

Massachusetts currently has 591,000 acres of wetlands. They store an estimated 190 million tons of SOC, equivalent to 698 million tons of carbon dioxide. Per-acre SOC stocks of wetlands in Massachusetts are on average six times as high as forests. Wetlands are the third largest land cover class, but have the highest carbon stocks.

Protecting and Enhancing SOC in Wetlands

Protection. Protecting wetlands is critical, as restored wetlands and constructed wetlands have significantly lower levels of soil C after 20 years—53% on average—as compared to natural wetlands, and there is not consensus on whether they will ever be able to achieve the same level of soil carbon as natural wetlands (Yu et al., 2017). The lower soil carbon ceiling combined with the exceptional cost of wetland restoration—DER staff estimate that freshwater wetlands cost $20,000 per acre to restore—means that protecting wetlands from development, disturbances, degradation, and invasive species is a top management priority.

Restoration. There is a tremendous potential for wetland restoration in Massachusetts. One restoration strategy, called "re-wetting," restores the original hydrology of a wetland by blocking or removing the drainage system that was originally put in place to drain it. Although this strategy may lead to an initial bump in methane emissions from wetlands, studies have suggested that these emissions rates decrease over time and become consistent with natural wetland systems within a few years (IPCC, 2014; Joosten et al. 2016). Restoring natural hydrology is critical for effective wetland restoration and curbing the carbon dioxide emissions of drained wetlands. It also ensures that wetland ecosystems are more resilient and self-sufficient.

In freshwater wetlands, restoring hydrology may include installing weirs and blocking drains and canals, and filling ditches (Fennessy & Lei, 2018). In freshwater systems, cranberry bog restoration is a critical SOC-building opportunity, with thousands of acres of high- and medium-priority wetlands identified for restoration statewide (Hoekstra et al., 2020). Other inland restoration is not included in the BMP Adoption Scenarios below due to lack of data, but further research is suggested in order to fully understand the potential for implementation of these practices. A final freshwater restoration opportunity identified by DER is dam removal. While there are more than 3,000 dams in MA, more research is needed to identify the SOC potential and timeline of this activity.

In coastal wetlands, restoring hydrology often includes restoring the full range of tidal flows in order to promote vegetation development and sediment trapping (Fennessy & Lei, 2018). In Massachusetts, DER estimates that as much as 80 to 90% of coastal wetlands have impacted tidal flows due to development and other disturbances. As a result, restoring natural hydrology is a key priority of DER's restoration efforts in both inland and coastal wetland ecosystems (call with DER staff, June 15, 2020).

Creation. Where protection and restoration are not possible, a new wetland can be created to provide some of the ecosystem services provided by natural or restored wetland ecosystems. It can be difficult to create effective and appropriate hydrology in created systems, and as a result, it can be challenging to shift vegetation closer to natural systems (Kentula, 2002). Additionally, costs of wetland creation can be 15 times more than those of wetland restoration. Further, replacement of the carbon sequestration function in freshwater-created wetlands can take decades to centuries to millennia to complete (Neubauer, 2014, Bridgham et al., 2014, Neubauer and Megonigal, 2015, Moomaw et al., 2018). Of note time is of less concern for creation of saltwater wetlands, which have a different soil biogeochemistry and can replace carbon sequestration functions fairly rapidly (Moomaw et al., 2018).


Silvio O. Conte National Wildlife Refuge, Hadley MA Credit Regenerative Design Group

Manipulation. Potential manipulations, of uncertain effectiveness, include use of GMO plants, and application of fertilizers, biochar, and/or humic acids.

BMP Adoption Scenarios

The scenarios in **Table 2.2** make assumptions about adoption of wetland BMPs and land cover change due to development. These are used to calculate the carbon flux from SOC in this land cover.

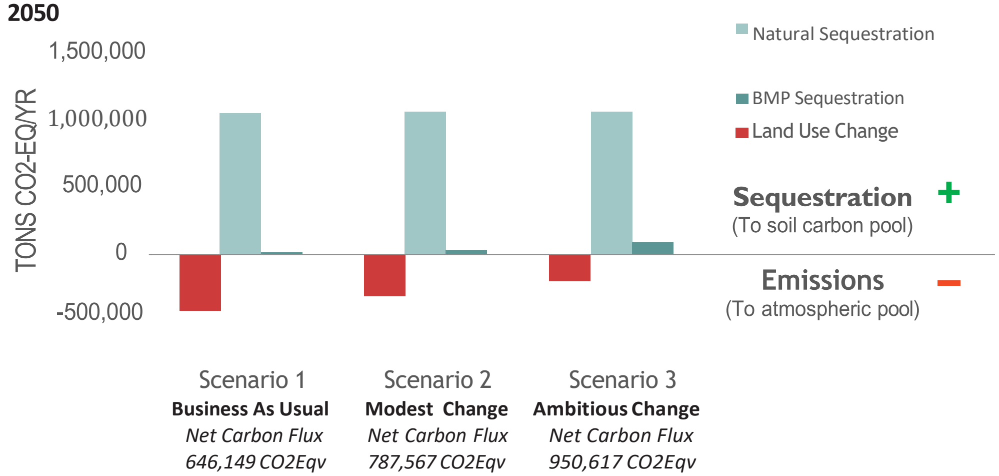
Annual Flux of Soil Organic Carbon in 2050

The annual flux of wetland SOC in 2050 (**Figure 2.2**) results in a net sequestration ranging from 175 to 259 thousand metric tons/yr. The natural carbon sequestration occurring in already existing wetlands provides the majority of this beneficial flux. The variance in flux largely comes from the differing amounts of wetland loss to land conversion. Because wetland soils are so carbon rich, protecting these ecosystems can have a powerful impact on carbon budgets.

Table 2.2 - Wetland Scenarios

Scenario	Adoption Assumptions	LUC Assumptions
1. Business as Usual	Adoption does not increase from current level.	100% of projected development related land conversion occurs
2. Modest Change	Restoration high-priority cranberry land at levels set by DER. Restoration of coastal wetlands grows at same rate as cranberry land in this Scenario. Other freshwater wetlands grow at half rate of cranberry land in this Scenario.	Smart growth achieves development goals, but reduces land conversion by 25%
3. Ambitious Change	Restoration of high- and medium-priority cranberry land at levels set by DER. Restoration of coastal wetlands grows at same rate as cranberry land in this Scenario. Other freshwater wetlands grow at half rate of cranberry land in this Scenario.	Smart growth achieves development goals, but reduces land conversion by 50%

Figure 2.2 - Wetland SOC Fluxes in Tons CO2-eq/yr. in 2050



Policies for Protecting and Enhancing Soil Carbon in Wetlands

1. Consider Developing State Wetland BMPs.

To ensure consistent management, a set of BMPs should be developed by DER, MassDEP, and CZM. While staff at DER and CZM recognize the importance of developing consistent BMPs for wetland management, a definitive list of wetland BMPs has not yet been developed. Upon development, DER, MassDEP, and CZM should undertake pilot projects to test and monitor potential BMPs for wetland management and restoration, which may require additional funding.

2. Increase Data Collection.

Given the high SOC density of wetland soils and their important role in sequestering carbon, there is a global need to increase data collection to better understand SOC trends and stocks (Holmquist et al., 2018; Nave et al., 2019). In Massachusetts, this could look like an investment in increased in-situ sampling of soil carbon.

3. Improve Mapping.

There is a need to update sea-level rise projections to account for the migration of wetlands and for future subsidence (conversation with DER, June 15, 2020). Additionally, the feasibility and maximum potential of inland wetland restoration is largely unknown. Mapping is needed to better understand where restoration opportunities exist, particularly for freshwater wetlands (conversation with DER, June 15, 2020).

4. Pursue Pilot Programs.

CZM and DER are undertaking a number of pilot projects to quantify the impacts of wetland restoration efforts. Early indications suggest that these efforts are successful. As a result, increased effort to pilot, learn, scale, and replicate these critical pilot program cycles is recommended (conversation with DER, June 15, 2020). Of note, implementing this will require an increase in resources, including funding.

5. Increase Restoration Efforts.

While preserving wetlands is the most effective strategy for preserving soil carbon, given the scale of wetland degradation restoration efforts are critical as well. This is because of the number of degraded wetlands across the Commonwealth that could potentially be restored. Of note, implementing this recommendation would require increased funding. The cost of restoration at the state level is currently approximately $20,000 per acre for cranberry bogs (conversation with DER, June 15, 2020), providing a sense of scale.

6. Focus Restoration Efforts on Restoring Hydrology.

Restoring hydrology should be the guiding principle as it is critical for building SOC and improving the self-sufficiency of the ecosystem (conversation with DER, June 15, 2020).

7. Consider Developing a Credential and/or Training Requirement for Wetland Development.

Implementation of a training requirement for wetland development would aim to ensure wetland restoration and creation projects consider and fully account for site hydrology and soil science. Certification could be administered by the state or a third party.

8. Additional Research.

There is a need for incorporation of decomposition and other biogeochemical mechanisms into blue carbon models to improve future predictions of SOC stocks (Spivak et al., 2019) and better understanding and predicting the magnitude of methane emissions in restored wetland ecosystems (Bossio et al., 2020). In addition, sea-level rise and warming temperatures not only complicate future projections of SOC stocks, but they are also estimated to release 150 million to 1.02 billion metric tons of CO_2 per year globally (Pendleton et al., 2012), making them a critical area for future research and improved modeling. Additional research is also needed to understand the full potential of dam removal and non-cranberry-bog freshwater restoration practices.

The Division of Ecological Restoration (DER) has done many freshwater, non-cranberry restoration projects and research could focus on monitoring before and after conditions of DER projects.

Recommendations

Set A Goal of No Net Loss. Accelerate Restoration and Adaptation Efforts.

Wetlands are valued and protected in Massachusetts, as evidenced by the Wetlands Protection Act and the work of Conservation Commissions, across the State. However, the dynamics and complexities of the ecosystem services they provide—and their role in climate change mitigation and adaptation—aren't fully accounted for in existing legislation, policy, replication practices, and regulation. Priority issues and actions identified during this planning process aim to bring wetlands to the forefront as vital contributors to state and regional climate resilience. The recommendations below are intended to increase awareness and action at all levels to minimize disturbance of wetland soils and hydrology that supports the function of these important ecosystems and the values they provide.

Tidmarsh - Plymouth, MA Photo Credit: Mass DER

Land Conversion

W1- Review and propose updates to standards, practices, and enforcement measures to improve WPA compliance and efficacy.

a. Provide for additional DEP Circuit Riders to support local Conservation Commissions.

b. Local Bylaws: Indirectly enhance by seeking updates to the Massachusetts Association of Conservation Commissions (MACC) Model bylaw, MACC Wetlands Buffer Zone Guide, and enforcement guidance.

c. Policy - Updates to the WPA and local bylaws: create a work group to examine the following areas and make recommendations for improvements.

   i. Seek to reduce the scale of by-right development of jurisdictional wetlands to zero square feet.
   ii. Soil function and structure as requirements of replication success.
   iii. Consider updates to the WPA and its regulations or development of guidance for the WPA that can focus on documenting how implementation of the Act and Regulations can benefit the climate resiliency of nearby human and natural communities {e.g., via flood and stormwater reduction, increased biodiversity, etc.).
   iv. Consider updates to the WPA and its regulations or development of a guidance document that accounts for carbon storage and sequestration, connects protection of wetlands to climate mitigation, and accounts for climate resiliency functions, such as provision of cooling to surrounding areas.

W2- Review and propose updates to regulations that protect the structure and function of wetland soils and the ecosystems they support.

a. Study of the effects of buffer size and composition on wetland soil health/ general wetland function. The MACC Wetlands Buffer Zone Guidebook references some relevant literature in this regard, but additional research and study is warranted.

b. Explore expansion of jurisdictional protections to wetland buffer zones and contributing areas as defined in the Wetlands Protection Act. Explore alternative approaches as well, including increasing the standard statewide buffer zone or requiring delineation and protection of contributing upland areas.

c. Update MACC's model wetland bylaw by incorporating soil health measures and standards.

d. Develop State technical assistance programs that support development of healthy soil zoning.

e. Provide resources to expand municipal adoption of effective performance standards that protect existing wetland soils and their ecosystem services (including carbon stocks and sequestration capacity) and contributing upland areas. Approaches could include grants for technical assistance to develop local ordinances.

W3- Consider updates to design standards, regulations, construction practices, and oversight to ensure replication and restoration efforts are effective and successful at creating/regenerating healthy wetland soil conditions.

a. Practices:

i. Improve specifications for siting replication wetlands in areas that have proven supporting hydrology.
ii. Update guidance such that the construction process of replication wetlands minimizes disturbance to the surrounding area and preserves, to the greatest extent possible, the integrity of existing native vegetation and translocation of full wetland soil profile, including roots and living shrubs and herbaceous species from the impact area to the replication area where feasible. Removal or stockpiling of wetland soils from site should be avoided or minimized.

b. Policy + Education:

i. Consider developing continuing education and certification programming for all people engaged in projects with wetland disturbance, replication, and/or restoration.

ii. Encourage involvement by certified ecologists/ wetland scientists/soil scientists and/ or ecological restoration professionals to oversee and monitor wetland replication projects.

W4- Account for wetland-based emissions in all climate change policies and action.

a. Policy: Integrate likely emissions from conversion of wetland into the Global Warming Solutions Act Implementation Plan (Decarbonization Roadmap).

b. State Wetlands Protection Act: Explore updates to the WPA to include preservation of existing soil organic carbon stocks and sequestration capacity.

c. Local Bylaw: Establish regulations and Best Management Practices to minimize disturbance of wetland soils, wetland soil organic carbon, and the hydrology that supports the formation and retention of these.

W5- Accelerate peatlands restoration on retired cranberry lands.

Soil + Land Management

W7- Seek to revise management activities in wetlands including vegetation management, filling, dredging, or other modifications to hydrology so they account for the impacts to soil health such as additional carbon emissions, reduced sequestration, or increased sediment transport.

a. Require nature-based mosquito controls like culvert upgrades that allow fish passage into wetlands and restore hydrology.

b. Promote invasive species management that does not damage wetland soil health.

i. Research the effects of chemical and mechanical disturbance on soil health.
ii. Develop soil-smart BMP's for invasives management.
iii. Conduct training and outreach on these BMP's.
iv. Support municipal efforts to update bylaws to prevent vegetation and species management practices that negatively affect wetland soil function.

Natural Hazards + Climate Change

W8- Seek to accelerate proactive mitigation and adaptation measures for sea level rise and other flooding aimed at protecting and restoring soil-based ecosystem services.

a. Support salt marshes and other estuarine wetlands to adapt to sea level rise through natural and assisted accretion of sediment and migration inland over time.

b. Ensure wetlands have adequate vegetated buffers and healthy plant communities to stabilize during flood events.

c. Prioritize conservation, restoration, and expansion of wetlands and their vegetated buffers in flood-zones to help protect upland and developed soils from erosion and contamination from more frequent and intense flood events.

d. Develop enhanced policies and programs to accelerate coastal zone soil remediation efforts, especially for the managed retreat of facilities that handle hazardous materials, paired with coastal wetland restoration.

Wetlands References

Anderson, Frank E., Brian Bergamaschi, Cove Sturtevant, Sara Knox, Lauren Hastings, Lisamarie Windham-Myers, Matteo Detto, et al. 2016. "Variation of Energy and Carbon Fluxes from a Restored Temperate Freshwater Wetland and Implications for Carbon Market Verification Protocols." Journal of Geophysical Research: Biogeosciences 121 (3): 777–95. https://doi.org/10.1002/2015JG003083.

Bayraktarov, Elisa, Megan I. Saunders, Sabah Abdullah, Morena Mills, Jutta Beher, Hugh P. Possingham, Peter J. Mumby, and Catherine E. Lovelock. "The Cost and Feasibility of Marine Coastal Restoration." Ecological Applications 26, no. 4 (2016): 1055–74. https://doi.org/10.1890/15-1077.

Bossio, D. A., S. C. Cook-Patton, P. W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, et al. "The Role of Soil Carbon in Natural Climate Solutions." Nature Sustainability 3, no. 5 (May 2020): 391–98. https://doi.org/10.1038/s41893-020-0491-z.

Bridgham, Scott D., Tim R. Moore, Curtis J. Richardson, and Nigel T. Roulet. "Errors in Greenhouse Forcing and Soil Carbon Sequestration Estimates in Freshwater Wetlands: A Comment on Mitsch et Al. (2013)." Landscape Ecology 29, no. 9 (2014): 1481–85. https://doi.org/10.1007/s10980-014-0067-2.

Burden, A., A. Garbutt, and C. D. Evans. 2019. "Effect of Restoration on Saltmarsh Carbon Accumulation in Eastern England." Biology Letters 15 (1): 20180773. https://doi.org/10.1098/rsbl.2018.0773.

Dahl, T. E. "Wetlands Losses in the United States 1780s to 1980s." Washington, D.C.: U.S. Department of Interior, Fish and Wildlife Service, 1990.

Davidson, Nick C. "How Much Wetland Has the World Lost? Long-Term and Recent Trends in Global Wetland Area." Marine and Freshwater Research 65, no. 10 (October 16, 2014): 934–41. https://doi.org/10.1071/MF14173.

Davies, Gillian, PWS, SSSSNE, NHCWS, CESSWI | Senior Ecological Scientist, Associate, BSC Group Inc. and Visiting Scholar, Global Development and Environment Institute, Tufts University. President 2016-2017, Society of Wetland Scientists.

Fennessy, S.M., and G Lei. "Wetland Restoration for Climate Change Resilience." Gland, Switzerland: Ramsar Convention Secretariat, 2018.

Holmquist, James R., Lisamarie Windham-Myers, Norman Bliss, Stephen Crooks, James T. Morris, J. Patrick Megonigal, Tiffany Troxler, et al. "Accuracy and Precision of Tidal Wetland Soil Carbon Mapping in the Conterminous United States." Scientific Reports 8, no. 1 (June 21, 2018): 1–16. https://doi.org/10.1038/s41598-018-26948-7.

IPCC. "2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands — IPCC." Switzerland: IPCC, 2014. https://www.ipcc.ch/publication/2013-supplement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories-wetlands/.

Joosten, Hans. "Peatlands across the Globe." Peatland Restoration and Ecosystem Services: Science, Policy and Practice, June 2016. https://doi.org/10.1017/CBO9781139177788.003.

Kentula, Mary. "Restoration, Creation, and Recovery of Wetlands Wetland Restoration And." United States Geological Survey, 2002.

Kroeger, Kevin D., Stephen Crooks, Serena Moseman-Valtierra, and Jianwu Tang. 2017. "Restoring Tides to Reduce Methane Emissions in Impounded Wetlands: A New and Potent Blue Carbon Climate Change Intervention." Scientific Reports. https://doi.org/10.1038/s41598-017-12138-4.

Miller, Benjamin. Global Warming Data Analyst at Massachusetts Executive Office of Energy and Environmental Affairs. Personal Communication. April 13, 2020.

Moomaw, William, Gail Chmura, Gillian Davies, Max Finlayson, Beth Middleton, Sue Natali, James Perry, Nigel Roulet, and Ariana Sutton-Grier. 2018. "Wetlands in a Changing Climate: Science, Policy and Management." Wetlands 38 (April): 1–23. https://doi.org/10.1007/s13157-018-1023-8.

Nahlik, A. M., and M. S. Fennessy. "Carbon Storage in US Wetlands." Nature Communications 7, no. 1 (2016): 13835. https://doi.org/10.1038/ncomms13835.

Nave, L. E., K. DeLyser, P. R. Butler-Leopold, E. Sprague, J. Daley, and C. W. Swanston. "Effects of Land Use and Forest Management on Soil Carbon in the Ecoregions of Maryland and Adjacent Eastern United States." Forest Ecology and Management 448 (September 15, 2019): 34–47. https://doi.org/10.1016/j.foreco.2019.05.072.

Nave, Lucas E., Paul E. Drevnick, Katherine A. Heckman, Kathryn L. Hofmeister, Timothy J. Veverica, and Christopher W. Swanston. "Soil Hydrology, Physical and Chemical Properties and the Distribution of Carbon and Mercury in a Postglacial Lake-Plain Wetland." Geoderma 305 (November 1, 2017): 40–52. https://doi.org/10.1016/j.geoderma.2017.05.035.

Neubauer, Scott C. "On the Challenges of Modeling the Net Radiative Forcing of Wetlands: Reconsidering Mitsch et Al. 2013." Landscape Ecology 29, no. 4 (2014): 571–77. https://doi.org/10.1007/s10980-014-9986-1.

Neubauer, Scott C., and J. Patrick Megonigal. "Moving Beyond Global Warming Potentials to Quantify the Climatic Role of Ecosystems." Ecosystems 18, no. 6 (2015): 1000–1013. https://doi.org/10.1007/s10021-015-9879-4.

Paustian, K. "Soil: Carbon Sequestration in Agricultural Systems." (2014): 140-152.

Pendleton, Linwood, Daniel C. Donato, Brian C. Murray, Stephen Crooks, W. Aaron Jenkins, Samantha Sifleet, Christopher Craft, et al. "Estimating Global 'Blue Carbon' Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems." Edited by Simon Thrush. PLoS ONE 7, no. 9 (September 4, 2012): e43542. https://doi.org/10.1371/journal.pone.0043542.

Rhodes L. 2018. Wetland Replacement in Massachusetts. ACEC Energy and Environment Committee Meeting. https://files.engineers.org/file/2018-12-04-MassDEP-Wetland-Mitigation-In-MA-ACECMA-Energy-And-Envir-Aff-Comm.pdf

Rhodes L, McHugh M, Gruszkos T. 2019. Inland and Coastal Wetlands of Massachusetts, Status and Trends. Mass DEP.

Spivak, Amanda C., Jonathan Sanderman, Jennifer L. Bowen, Elizabeth A. Canuel, and Charles S. Hopkinson. "Global-Change Controls on Soil-Carbon Accumulation and Loss in Coastal Vegetated Ecosystems." Nature Geoscience 12, no. 9 (September 2019): 685–92. https://doi.org/10.1038/s41561-019-0435-2.

Torio, Dante D., and Gail L. Chmura. "Assessing Coastal Squeeze of Tidal Wetlands," 2013. https://doi.org/10.2112/JCOASTRES-D-12-00162.1.

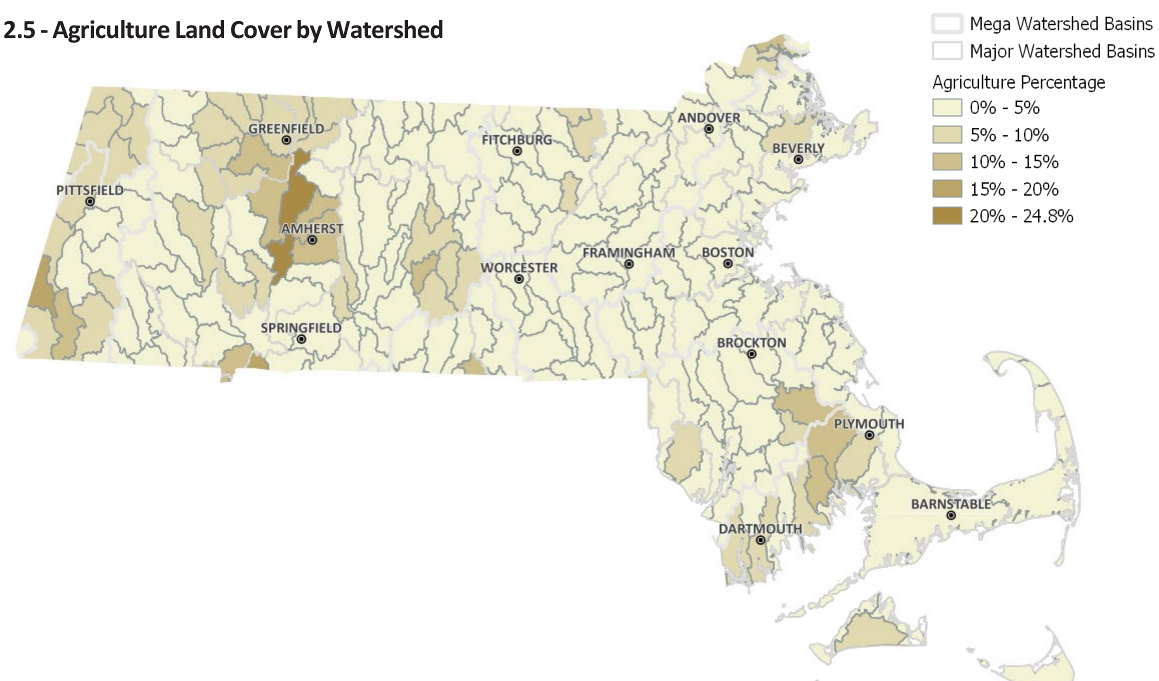
Yu, Lingfei, Yao Huang, Feifei Sun, and Wenjuan Sun. "A Synthesis of Soil Carbon and Nitrogen Recovery after Wetland Restoration and Creation in the United States." Scientific Reports 7, no. 1 (August 11, 2017): 1–9. https://doi.org/10.1038/s41598-017-08511-y.

Zomer, Robert J., Henry Neufeldt, Jianchu xu, Antje Ahrends, Deborah Bossio, Antonio Trabucco, Meine van Noordwijk, and Mingcheng Wang. "Global Tree Cover and Biomass Carbon on Agricultural Land: The Contribution of Agroforestry to Global and National Carbon Budgets." Scientific Reports 6, no. 1 (July 20, 2016): 1–12. https://doi.org/10.1038/srep29987.

Agriculture

Agriculture accounts for 4% of total land cover in Massachusetts, or 205,841 acres*. Farms operate in every county, and the northern Pioneer Valley and Plymouth and Dukes Counties have the highest percentage of active farms (2017 USDA Census of Ag, MDAR). The sub-watersheds around the towns of Hadley and Sunderland represent the most intense concentration of agriculture in the state, with over 20% of their lands actively farmed* ***(Map 2.5)****. There is strong support for Massachusetts-based agriculture, as evidenced by the work of Community Involved in Sustaining Agriculture (CISA), the MA Farm Bureau, the MA Food System Collaborative, and others. Despite that, development and economic pressures persist, as do barriers to widespread adoption of healthy soils practices. In order to ensure Massachusetts' agricultural soils can continue producing into the future, efforts to protect farmland and accelerate the adoption of soil-smart management practices are priorities.*

Map 2.5 - Agriculture Land Cover by Watershed

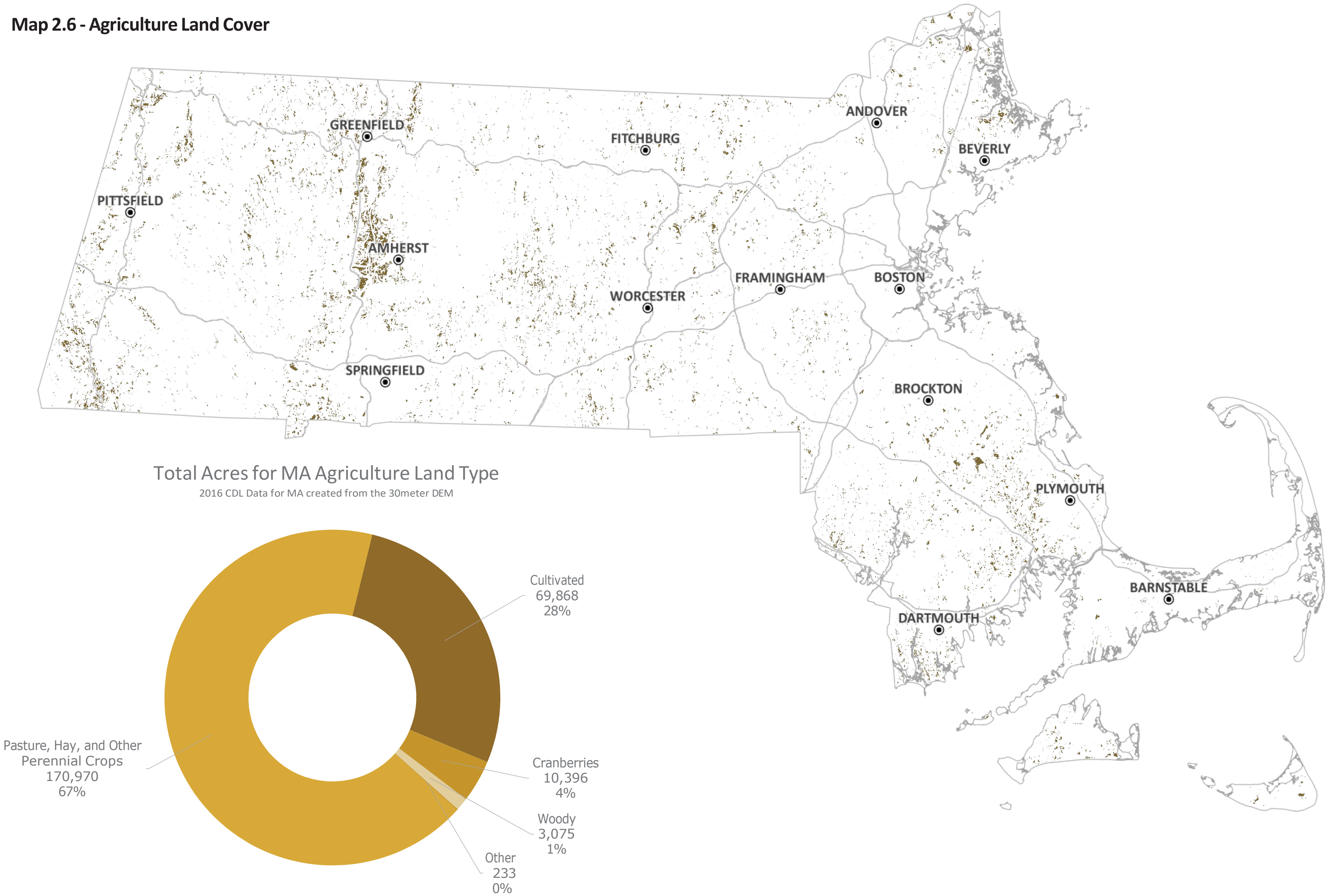


Patterns and Characteristics

Agricultural soils exhibit combinations of physical, chemical, and biological characteristics that make them well suited for growing food, fiber, feed, and forage, (see subclasses of agriculture on page 67). The NRCS identifies 1.5 million acres of soils in Massachusetts in the Soil Survey as suitable for agriculture, classified as Prime Farmland, Farmland of Statewide Importance, or Farmland of Unique Importance. Based on the land cover analysis used in this report, roughly half of those acres are covered by forests and trees, followed by turf + ornamental landscapes (207,000 acres), impervious (157,000 acres), agriculture (145,000 acres), and wetlands (85,000 acres) A composite analysis of the New England Land Futures scenarios reveals that 56,894 acres of these prime soils are likely to be developed by 2050. This includes approximately 36,000 acres of actively farmed prime soils with the rest in other land covers.

One challenge in quantifying the impact of agricultural practices on soil health in Massachusetts is the difference in sources and methods of collecting data. The USDA operates a National Agricultural Statistics Service (NASS) that conducts a census of

Map 2.6 - Agriculture Land Cover



agriculture every five years and publishes the results by state. Land Use/ Land Cover data available through Mass.gov has categorized land in agricultural use (**Map 2.6**) through the visual analysis of satellite photos. The difference in data gathering—self-reported by landowners or digitally analyzed—results in some discrepancy of information.

The 2017 Agricultural Census cites that the 491,000 acres of farmland in the State produce fruit, vegetables, dairy, livestock, greenhouse, and nursery crops valued at over $475 million (2017 Ag Census). However, according to the 2016 Land Cover data available for GIS analyses (and used in this report), agriculture accounts for 205,841 acres, 4% of the total land cover. The majority of this difference can be attributed to the forested acres of land owned by farmers being counted as 'farmland'. These forest holdings, including timber land and maple sugar bushes, make farmers as a group the single largest forest holders in the State.

A small portion of the acreage gap can also be attributed to other agricultural lands in fallow or other uses not easily identified from satellite imagery, such as grasslands and shrublands. Both the USDA census information and the Land Cover information are used in this section of the Healthy Soils Action Plan, where most relevant.

Subclasses of Agriculture

Permanent Pasture and Hay. Perennial production systems that maintain permanent cover of grass and herbaceous perennials, typically managed for animal forage, account for 170,970 acres (2016 CDL) of agricultural land cover. No region or county dominates hay and pasture but Berkshire and Worcester each have around 20% of the permanent pasture and hay acres.

Cultivated cropland. Row crops like vegetables, grains, and silage corn along with other crops that typically depend on regular cultivation, tillage, or other soil disturbance occupy 69,868 acres (2016 CDL). Soils in these crop systems are typically tilled or otherwise disturbed on at least an annual frequent basis. According to the Crop Land Data layer more than half of those acres were considered fallow in 2016 (35,877 acres). Much of the fallow land is associated with cranberry growing regions. The non-fallow half of the cultivated acres are dominated by Franklin and Hampshire counties each with about a quarter of the acres.

Cranberries. Massachusetts has 10,396 acres (2016 CDL) of cranberries, a relatively unique crop requiring very specific soil and hydrology conditions (see Wetlands section Soil + Land Management:

Woven Roots Farm - Tyringham, MA Photo Credit: David Edgecomb

Agriculture on page 53). Over 90% of cranberry acres are in Plymouth County.

Agroforestry and Perennial Crops. The subclass produces a wide variety of crops currently covering 2,746 acres (2016 CDL) of soils some of those soils are unsuitable for annual tillage. These include systems familiar to most people such as orchards, berry operations, and Christmas tree farms. This category also includes less familiar systems like silvopasture, coppice, and nut crops. 60% of the acres are in Worcester and Middlesex counties. The Pioneer Valley counties (Franklin, Hampshire and Hampden) account for another 24%.

Vulnerabilities

Farm Viability

Preserving and managing healthy soils on Massachusetts' farms is only one piece of the complicated puzzle of farm viability. American Farmland Trust defines farm viability as the ability for a region's "agricultural land base to retain adequate soil quality and withstand development pressures; for its farmers to be diverse and remain equipped for land transfer; and for its farms to sustain financially profitable operations that anticipate the market and climate challenges ahead" (Pottern et al, 2020, p.29). Agricultural sectors like dairy, maple syrup production, and cranberry farming have been practiced for generations, and contribute greatly to the State's farming identity and beloved landscapes—and all face decline due to market and climate challenges (USDA, 2017). Small and mid-sized farms more common to Massachusetts "are constrained in their ability to scale up" (Pottern et al, p.31) and, even with the successes of some land access programs, it is still very challenging for new farmers to acquire land (Pottern et al, 2020). Healthy soils programs, however, can play a role in farm viability, particularly if they can support diversification and payment for ecosystem services. Case study analysis by American Farmland Trust has found that farmer adoption of healthy soils practices (including increased cover cropping and conversion to strip tillage or reduced tillage practices) saves farmers money, averaging $36/acre in fertilizer use reduction and $35 per acre on machinery use, fuel and labor expenses (American Farmland Trust, 2020).


North Plain Farm, Great Barrington MA Photo Credit: MA NRCS

Land Conversion

Residential and Commercial Development. Much of the state's farmland is located along scenic byways and around growing communities. The visibility and aesthetic appeal of these farms make them highly valuable contributors to the rural New England character so beloved by Massachusetts' residents and visitors. The proximity of many farms to roads and growing towns also expose these farms and their soils to the risk of residential and commercial development. At $11,100 per acre, Massachusetts has the fourth highest farm real estate values in the country. Between 2001-2016, 14,300 acres of Massachusetts' farmland was converted to urban and highly developed use, while 12,800 acres were considered threatened by low-density residential development (Farms Under Threat, 2020). Permanently protecting farmland is the best way to prevent loss of soil health due to land conversion. Today, less than 75,000 farmland acres have Agricultural Preservation Restrictions (communication with Ronald Hall, APR Program Coordinator).

Ground-Mounted Solar Development. Farmland is also actively being lost to ground-mounted solar development. State incentive programs have produced 1,210 solar installations, converting g 6,500 acres of land, over half of which (3,650 acres) were on agricultural or forested lands (Pahlavan, 2019). Mass Audubon and other environmental groups strongly support the State's transition to clean energy, but also support revision of the Department of Energy Resources (DOER) solar financial incentive program (SMART) to increase incentives for projects on rooftops, parking lots, and other already altered sites and to reduce or eliminate incentives for solar development on natural and working lands. DOER is evaluating the impacts of these program changes to explore incorporation into future program updates and is in ongoing contact with these environmental groups as it seeks to strike an appropriate balance between encouraging needed solar facilities and minimizing impact to natural and working lands (communication with Mass Audubon).

Climate Change + Natural Hazards

Many of the Commonwealth's richest agricultural soils are located in the floodplains of rivers, streams, and coastal areas. The loamy texture and rich nutrient profile of these soils, built by millennia of flood deposits and enrichment by native vegetation, have helped produce crops for hundreds of years, before and after colonization. However, the position of these farms exposes them to larger and more frequent floods, with risks of inundation, erosion, and significant economic losses. GIS analysis for HSAP shows that 17% of cultivated land is in the 100-year flood plain. It's important to note, however, that this doesn't include Franklin County, which is missing FEMA data.

Pioneer Valley farmers got a glimpse of what increased precipitation and stronger storms could look like in August 2011, when Hurricane Irene passed directly over the Connecticut River Valley, causing some farms to lose as much as 95% of their crops (Appleton, 2011). Yellen et al (2014) states, "sediment yield...from the Deerfield River, a steep tributary comprising 5% of the entire Connecticut River watershed, exceeded at minimum 10–40 years of routine sediment discharge and accounted for approximately 40% of the total event sediment discharge from the Connecticut River." Quantifying soil loss due to flood events is less straightforward than that of crop loss, but still reveals the enormous effect of storm and flood damage on soils.

Soil + Land Management

In agriculture, barriers to adoption typically fall into three categories—science, economics, and policy. The study of soil health is ever evolving, and reliably measuring soil health is tricky. As a result, farmers aren't always privy to proven, regionally specific strategies for their farms. Economically, because many farms operate on thin margins, the potential burden of implementing soil health practices—which may require new equipment and increased seed and labor costs—can be a significant financial hurdle. Programs to pay farmers who commit to implementing healthy soils practices could help offset these costs. Both Maryland (The Cover Crop Grant) and New York (Healthy Soils NY) have piloted programs that pay farmers $50/year on a per acre basis. Other international healthy soils programs pay for measurable performance in the form of increased SOC at rates from $50-$200/ton. After consulting soil experts and the literature, TNC estimated that implementing healthy soils practices on corn, soy and wheat crops alone could mitigate 25 million tons of greenhouse gas emission, reduce 344 million pounds of nutrient loss and eliminate 116 million metric tons of soil erosion and create 2.6 million acre-feet of available capacity in cropland soils. An additional barrier cited during HSAP Listening Sessions was that many grant programs have minimum acreage requirements that don't accurately reflect the average size of Massachusetts farms, thereby disqualifying small farmers from applying.

Several chapters of the Northeast Organic Farming Association (NOFA) recently conducted a series of round-table discussions

in six Northeast states, with a total of 192 farmers. They found that regionally, barriers to adoption echo those found nationally, with an additional emphasis on the need for more education and technical support. A report by NOFA Mass (https://nofa.org/organizing-for-soil-health/), will share the results of these discussions. Initial findings are summarized below:

» Farmers need more access to education and technical support and prefer learning from other farmers. Specific support areas mentioned were:

  a. Increasing efficiencies within healthy soils practices.

  b. Scaling up healthy soils practices.

  c. Long-term soil and water quality testing and monitoring.

» The need for incentives was also widely discussed, but opinions varied on methods, with some farmers specifically expressing support for payment for practice models, while others felt payments should be outcome-based.

» Farmers also discussed the need for more investment in local/regional food systems and smaller-scale farms more typical of the region—and showed interest in grants/funding that helps pay for equipment, provide a buffer while transitioning to new practices, purchase cover crops, and implement perennial buffer strips and windbreaks.

Tools for Measuring Soil Health

Approaches for evaluating on-farm soil health vary widely and depend on a farm's goals, desired methodology, cost, and confidence. Not all on-farm soil health indicators apply to all farms. For simple agricultural systems like large-acre commodity crop agriculture, days in living cover (established via satellite land cover analysis) combined with modeling tools like USDA's Comet Farm can provide relatively high-confidence estimates of agricultural soil health trajectories at a relatively low cost. However, such tools are not an ideal fit for the diversified and small-farm environment of Massachusetts agriculture. More sensitive technological approaches such as remote sensors for soil health indicators are under development, but currently the best available approaches to soil health measurement fit broadly into two approaches: lab assessments and field assessments. Generally, lab assessments have a higher confidence level, but both approaches can have increased confidence with greater sampling density and by sample design. (See Quick Carbon's Stratifi tool, currently under development).

Farmers and third-party advisors can get a reasonable snapshot of soil health from any reputable lab SOC report, but it is worth noting that different labs use different methodologies for quantifying soil organic matter, and results are not only variable across different labs but variable within the same lab from the same aggregated sample. Furthermore, soil organic matter levels will fluctuate by the time of year and are more or less dynamic by soil type (sandy soils lose organic matter more rapidly than clay soil, for example). Soils are dynamic ecosystems that exist in relation to their plant communities, so soil organic matter has some limitations as a sole metric for evaluating soil health. Therefore, most soil health assessment involves some level of physical indicators and measure of soil characteristics and plant community.

Open TEAM (Open Technology Ecosystem for Agricultural Management), has classified three tiers of Field Protocols for soil health assessment according to confidence and use, which is inclusive of a broad array of protocols used by organizations, agencies, universities and researchers:

Tier 1, Farm Level:

Site-specific decision support tools designed to help farmers and 3d-party technical advisors (NRCS, NOFA, Extension) to make in-field evaluations based on physical soil properties, soil surface and crop characteristics, and ecological indicators. Examples of field protocols are the NRCS Cropland In-Field Soil Health Assessment Worksheet, Visual Assessment of Soil Structure, and the NOFA Soil Carbon Proxy Tests, which include quantifications or record keeping protocols for many of the indicators listed in **Table 2.3 - Soil Health: Indicators + Measurements**. Tier one tests are generally conducted once annually with one sample per management zone (i.e. separate fields with different enterprises or management practices).

Tier 2, Cost Effective Soil Carbon Quantification:

Field-level decision support tools plus lab verification of soil organic carbon for research purposes and for basic soil health and soil carbon enhancement /incentive programs. Tier 2 involves conducting Tier 1 methods with the addition of bulk density and lab-verified soil carbon testing to an agreed-upon depth (dry combustion or GC/MS) taken from multiple soil samples using a stratified sampling design. This level can be achieved using a stratification tool and the Cornell Comprehensive Assessment of Soil Health (CASH) or another lab using either DC or GC/MS to establish SOM levels.

Tier 3, Research:

Ground-testing of technologies, decision support tools and carbon quantification tools. This tier includes metadata collection and detailed, precise research protocols including high density sampling, multiple depth sampling and selective deep core sampling.

Microbial Analysis:

Soil microscopy and food web analysis are another sector of soil health analysis that is less widely adopted for practical purposes. Generally microscopy is performed by a third-party private consultant but tools like the Microbiometer is a commercially-available smart-phone tool and test kit that offers basic readings on microbial volume and fungal-to-bacterial ratio.

Soil respiration tests are another way to evaluate soil microbial activity and are a useful measurement of soil health when conducted in a laboratory, but such tests have limited useful application outside of the laboratory due to their results variability in the absence of rigidly temperature controlled environments.

Comprehensive Assessments:

There are some labs that offer a mix of soil organic matter evaluation, nutrient analysis, and limited evaluations of physical and microbial tests. Labs include the Cornell Cooperative Extension’s Comprehensive Assessment of Soil Health and the University of Maine, which offers a Soil Health / Soil Quality add-on to their standard soil test package.

Spotlight on Soil Organic Carbon

Agricultural soils are not particularly high in carbon. The average agricultural soil has lost 25-75% of its carbon, compared to its pre-agricultural state. Globally, cropland and grazing land store 5% of global soil organic carbon but occupy 38% of the world's land (Lal 2014). In places like Indonesia and Brazil, clearing forests for farmland is a major source of emissions, though this is not a major issue in Massachusetts at this time.

Massachusetts Agricultural SOC

Harvard Forest's New England Landscape Futures Explorer projects that MA farmland will only fall by several hundred acres from its current 205,841 acres by 2050. This is based on an assumption that development will happen on forests rather than farmland, though HSAP is not confident that this is the case. The current SOC stock in agricultural land is estimated at 9 million tons, equal to 34 million tons of carbon dioxide. Agriculture is the smallest of HSAP's five land cover categories and has the smallest total stock.

Woven Roots Farm - Tyringham, MA Photo Credit: Jen Salinetti

As of 2020, agricultural land is subdivided into annual cropland (29%), perennial cropland (6%), and pasture/hayland (65%) (USDA NASS). Per-acre stocks are highest in perennial cropland, followed by pasture/hayland, with annual cropland having the lowest stocks.

Protecting and Enhancing SOC in Agriculture

Conservation Agriculture

The annual cropping system combines cover crops, reduced tillage, and crop rotation. It is widespread globally, and practiced on an estimated 26% of Massachusetts cropland today (USDA NASS). Conservation agriculture practices that are incentivized by NRCS programs include Cover Cropping (NRCS practice class 340), Tillage Reduction (329) and Residue and Tillage Management, Reduced Till (345) Funding is also available for tillage reduction equipment via MDAR's ACRE grant program.

Organic Annual Cropping

Organic systems in Massachusetts not only avoid synthetic fertilizers but also incorporate cover crops and crop rotations. An estimated 3% of cropland in the Commonwealth is organic (USDA NASS). Financial assistance for organic practices and transition are available through NRCS EQIP contracts.

Protective Agroforestry Systems

Agroforestry systems integrate trees with the crop and/or livestock production, and sequester carbon both as SOC and in aboveground biomass. Protective systems involve tree plantings at the edges of fields (shelterbelts) and along streams and rivers to protect water quality (riparian buffers). These practices occupy about 0.4% of Massachusetts cropland but are growing steadily (USDA NASS). Funding is available for windbreak/shelterbelt establishment (380), riparian herbaceous cover (390), riparian forest buffer (391).

Alley Cropping

This class of agroforestry system integrates trees (for timber, fruit, or fertilizer) with annual crops. An innovative first wave of farms is currently establishing alley cropping systems in the Commonwealth. NRCS funding is not yet available for this practice in Massachusetts, but MA NRCS can adopt the associated conservation practice if there is interest from farmers. MA NRCS soil health staff are currently reviewing how other states are using this practice.

Managed Grazing

There are many grazing systems that increase SOC in pastures, involving adaptive management including rotations, changes to stocking rates, and resting periods for pasture regrowth. Managed grazing is practiced on an estimated 19% of Massachusetts grazing land (USDA NASS). There is robust scientific debate over the potential of Adaptive Multi Paddock (AMP) grazing systems, which may eventually be shown to have much higher sequestration rates than standard managed grazing. Financial assistance for grazing plans and improved grazing management are available through NRCS EQIP contracts (528).

Silvopasture

Silvopasture is another agroforestry system that involves planting trees in an established pasture. This practice shows impressive sequestration both of SOC and aboveground woody biomass (a variant involves thinning forests to create silvopastures, presumably with an attendant loss of SOC). Like alley cropping, a vanguard of Massachusetts farmers are beginning to adopt this practice. Funding is available for tree establishment in pastures—Silvopasture (381), however, MA NRCS does not fund the thinning or clearing of trees to establish pasture.

Photo Credit: Jim Robinson, USDA-NRCS

Table 2.3 - Agriculture Scenarios

Scenario	Adoption Assumptions	LUC Assumptions
1. Business as Usual	Adoption does not increase from current level.	100% of projected development related land conversion occurs
2. Modest Change	Conservation agriculture grows at rate used for Project Drawdown's 1.5˚ scenario. Organic continues to grow at current rate. Protective agroforestry systems grow at half current rate. Alley cropping and silvopasture reach ¼ the current extent of organic. Managed grazing grows at rate used for Project Drawdown's 1.5˚ scenario.	Smart growth achieves development goals, but reduces land conversion by 25%
3. Ambitious Change	Conservation agriculture grows at the existing, rapid growth rate of no-till in the Commonwealth. Organic grows at 1.5 times its current rate. Protective agroforestry systems grow at current rate. Alley cropping and silvopasture reach the current extent of organic. Managed grazing grows at national growth rate.	Smart growth achieves development goals, but reduces land conversion by 50%

BMP Adoption Scenarios

Compared to other land covers, there is abundant data on the current adoption of BMPs in Massachusetts (**Table 2.3**). This includes historic growth rates, and aid to projecting future adoption. HSAP's three scenarios make assumptions about adoption of BMPs and land cover change due to development. These are used to calculate the carbon flux from SOC in this land cover.

SOC Fluxes in 2050

Fluxes from agriculture are very modest (**Figure 2.3**), not surprising given the small acreage in this land cover. Net gain is 7 to 22 thousand tons of SOC per year in 2050, with most of the impact coming from adoption of BMPs. Policy efforts to protect and enhance agricultural SOC should seek to minimize development and encourage adoption of BMPs. Encourage NRCS to prioritize carbon-friendly practices in allocation of EQUIP funds.

Figure 2.3- Agriculture SOC Fluxes in Tons CO2-eq/yr. in 2050

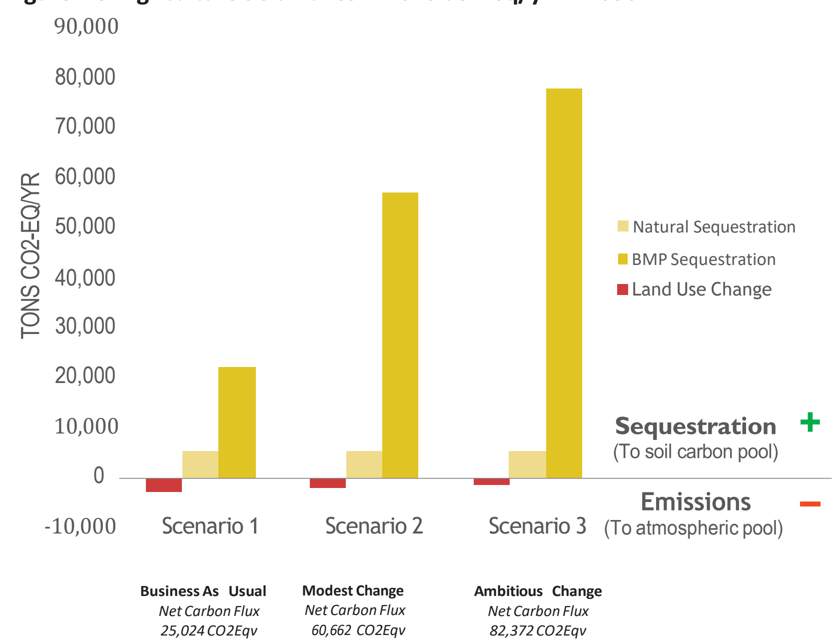



Photo Courtesy of MA NRCS

Recommendations

Protect farmland and incentivize healthy soils practices. *Because agricultural land represents a small percentage of land cover in the State, its contribution to climate change mitigation and adaptation—even with healthy soils practices—is arguably minimal, especially when compared to forests and wetlands. Of course, that shouldn't negate the role MA farming can and should continue to play in regional food production and security, habitat and biodiversity support, water quality, and local culture. Accelerated protection of farmland, adoption of healthy soils practices, and support for Massachusetts' farmers should all be ongoing priorities, as many reports cited in this Plan have concluded. Indeed, a commitment to farmers and farming that supports resilient landscapes and healthy soils in rural, suburban, and urban communities, may help to strengthen the role of MA agriculture in the regional food economy, and meet some of the goals laid out in The New England Food Vision.*

Photo Courtesy of MA NRCS

Land Conversion

A1- Seek, consistent with the land conservation goal of the Clean Energy and Climate Plan for 2025 and 2030, to permanently protect 30% of undeveloped Prime farmland soils and soils of statewide importance by 2030. As part of this effort, the state will seek to expand incentives and provide tools to encourage smart growth in less developed areas and incentives to expand housing in city and town centers and other developed areas with existing infrastructure.

a. Identify priority areas where agricultural soils are most vulnerable to development.

b. Programming

   i. Seek to expand the Agricultural Preservation Restriction program to protect additional farmland and to raise the cap on the Commonwealth Conservation Land Tax Credit to encourage more land donations.

   ii. Look to increase support to municipalities with high levels of conserved land, which would help to offset lost tax revenue.

c. Research the cost of permanent protection of all agriculturally significant soils and evaluate the benefits and impacts of conserving them.

A2- Seek to improve protection of farmland from single use solar development in future amendments to solar incentives (including ongoing evaluations of the efficacy of combined solar/farm installations).

a. Continue to incentivize solar development towards already developed lands where co-benefits are high such as parking lots, flat roofs, roadsides, and brownfields in future updates to solar incentives.

b. Evaluate multi-use solar development on agricultural lands on an ongoing basis and make adjustments to incentivize solar development with clear farm viability and soil health benefits.

c. Consider developing and issuing a new model bylaw for municipalities.

A3- Accelerate efforts to increase the viability of farm livelihoods.

a. Develop an explicit State-level goal for food production supported by economic programs/structures that incentivize farm production.

b. Support for regional buy-local efforts, like Communities Involved in Sustaining Agriculture and Buy Fresh Buy Local Cape Cod.

c. Strengthen Farm-to-Institution supports.

d. Develop statewide and RPA-scale emergency food system resiliency plans that include buying, aggregation, transportation, and distribution strategies for Massachusetts producers.

e. Support farm transition planning, land leasing programs, new farmer programs, and community farm development as a way to increase land access for potential producers.

Soil + Land Management

A4- Increase farmer enrollment and participation in existing programs that provide technical assistance, educational opportunities, and material support.

a. Enroll, by 2030, 50% of existing production acres in the new healthy soils management program to be created pursuant to the 2020 Economic Development Bill.

A5- Increase economic support in order to incentivize implementation of healthy soils practices.

a. Establish and fund Natural Resilience Plans that include building soil health. Look at providing financial incentives for farmers who commit to building soil health. Emphasize long-term programs + relationships.

b. Look at developing a pilot Healthy Soils Practices Program to pay farmers $50/ac/yr. who commit healthy soil practices.

c. Seek to increase or establish cost-sharing programs to assist farmers with training and equipment costs for transition to practices which increase soil health.

A6- Eliminate technical and knowledge barriers to adoption of practices which increase soil health.

a. Research:

i. Identify and study healthy soils practices for each subclass of agriculture that provides unequivocal financial benefit to farmers.

ii. Update grant funding eligibility for federal, state, and other conservation and agricultural programs to ensure that all healthy soil practices are effectively incentivized.

iii. Previously mentioned Healthy Soils Pilot Program: Prepare financial review of Massachusetts + regional farmers who've implemented HSP's. Disseminate findings and case studies featuring most promising HSP's.

b. Seek Additional Resources for the following:

i. Enhance the analytical capacity for measuring soil health in Massachusetts through purchase of additional equipment at the State Soil Laboratory.

ii. Increase support for educational programs, technical service, and targeted outreach efforts on the benefits, costs, and details of implementing healthy soils practices.

iii. Ensure that sufficient resources are provided to institutions and organizations that provide technical, educational, and other support to farmers in healthy soil practices including Agricultural Extension, Conservation Districts, private non-profits such as NOFA, and proven private consultants.

c. Education/Outreach:

i. Conduct Statewide multi-media awareness campaigns on soil health and its connection to community resilience, economic viability, and climate change. Provide landowners with 'what you can do' information. Support the development of certifications and training for soil health practitioners and technical service providers.

ii. Farmer-to-Farmer: Encourage farmer-to-farmer events, including “twilight talks”, that promote use of best practices.

Natural Hazards + Climate Change

A7- Increase monitoring + research of ongoing changes to agricultural soils from climate change.

A8- Incentivize integration of trees and other perennial crops into agricultural systems to increase resistance and resilience to more frequent droughts, floods, and extreme weather.

a. Increase farmer outreach and education on existing programs such as the NRCS Environmental Quality Incentives, that support tree plantings and other nature-based climate-resilience solutions around the edges of farms, including windbreaks, pollinator hedgerows, and riparian buffers.

b. Look at establish funding, in partnership with NRCS and other agencies, to incentivize alley cropping and pasture- to-silvopasture conversion.

c. Seek to develop state and local programs to incentivize reforestation of agricultural riparian

Photo Courtesy of MA NRCS

Agriculture References

American Farmland Trust. “Quantifying Economic and Environmental Benefits of Soil Health”. Retrieved from https://farmland.org/soil-health-case-studies-findings.

Appleton, John. “Hurricane Irene flooding devastates several Western Massachusetts farm crops” MassLive, August 2011.

Lal, Rattan. “Societal Value of Soil Carbon.” Journal of Soil and Water Conservation 69, no. 6 (November 1, 2014): 186A. https://doi.org/10.2489/jswc.69.6.186A.

Magdoff, Fred and van Es, Harold, 2010 “Building Soils for Better Crops”, Sustainable Agriculture Research and Education (SARE)

MassGIS (2019). 2016 Land Cover/Land Use. Retrieved from https://docs.digital.mass.gov/dataset/massgis-data-2016-land-coverland-use [Accessed May, 2019].

NRCS (2020). “Healthy Soils, Clean Water” and “Soil Health Checklist” outreach documents. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/.

Pahlavan, D. (2019). Solar Installation ILC Presentation. EEA GIS.

Pottern, Jamie B, and Laura N Barley, 2020 “Farms Under Threat: A New England Perspective,” Northampton, MA: American Farmland Trust

Project Drawdown (2020). Regenerative Annual Cropping. Retrieved from: https://www.drawdown.org/solutions/regenerative-annual-cropping.

The Nature Conservancy, “reThink Soil: A Roadmap to U.S. Soil Health”, Executive Summary, 2016.

USDA National Agricultural Statistics Service, 2017 Census of Agriculture. Complete data available at www.nass.usda.gov/AgCensus.

Yellen, B., J. D. Woodruff, L. N. Kratz, S. B. Mabee, J. Morrison, and A. M. Martini. “Source, Conveyance and Fate of Suspended Sediments Following Hurricane Irene. New England, USA.” Geomorphology 226 (December 1, 2014): 124–34. https://doi.org/10.1016/j.geomorph.2014.07.028.

Baldwin Hill APR Land; Photo Courtesy of MA NRCS

03 | Developed Lands

Recreational + Ornamental | Impervious-Dominated

Rose Kennedy Greenway, Boston - Photo Credit: Kindra Clineff

Developed Lands

Developed Lands are the diverse landscapes of our towns and cities, neighborhoods and campuses, and commercial and industrial centers. *The majority of these lands can be classified as either Recreational and Ornamental Landscapes or Impervious Dominated Landscapes. Counted together, these highly modified and heavily managed landscapes cover more than 17% of the Commonwealth (LULC 2016).*

These two land covers each have varied and distinct uses, development processes, management practices, and land use histories that result in a predictable range of soil health challenges. Unlike natural and working lands, the main driver of soil health in developed lands is the development process itself, rather than management practices. Conventional development practices result in the removal of most or all of the upper soil horizons and the vegetation that once grew there. This disturbance dramatically alters intrinsic soil characteristics, generally resulting in thinner upper soil horizons and more compacted conditions. Once development is completed, management can play a crucial role in the health of these soils, but only within the narrow margins of the new soil's dynamic properties.

The impacts of climate change, notably more frequent high-intensity rain events, amplify the challenges of diminished soil function in these landscapes. When developed, soils typically lose 25 to 60 percent of their total soil organic carbon and most of the soil structure of their A and B Horizons, resulting in a greatly diminished capacity to infiltrate stormwater. With this loss of soil function, engineered stormwater solutions become necessary.

Because of the current and growing extent of developed lands in Massachusetts—with Recreational and Ornamental Landscapes occupying 438,438 acres and impervious covering 475,033 acres (LULC 2016)—influencing the forces that shape soil function in these land types could have a powerful impact on the overall soil health of the Commonwealth. In the following two sections, these forces are explored more fully and a set of goals, actions, and strategies of improving soil health outlined.


Flash Flood, Dorchester, MA - Photo Credit: Adam Pianiezek

This includes the following priorities for improving soil health in developed lands:

- Explore establishment of post-construction soil performance standards or guidelines.
- Increase protection of soil, topography, and vegetation during construction.
- Incentivize smart-growth development/ redevelopment.
- Expand green infrastructure.
- Plant trees.
- Clean-up toxic soils.
- Expand adoption of best management practices.

The Impact of Development on Soil Health

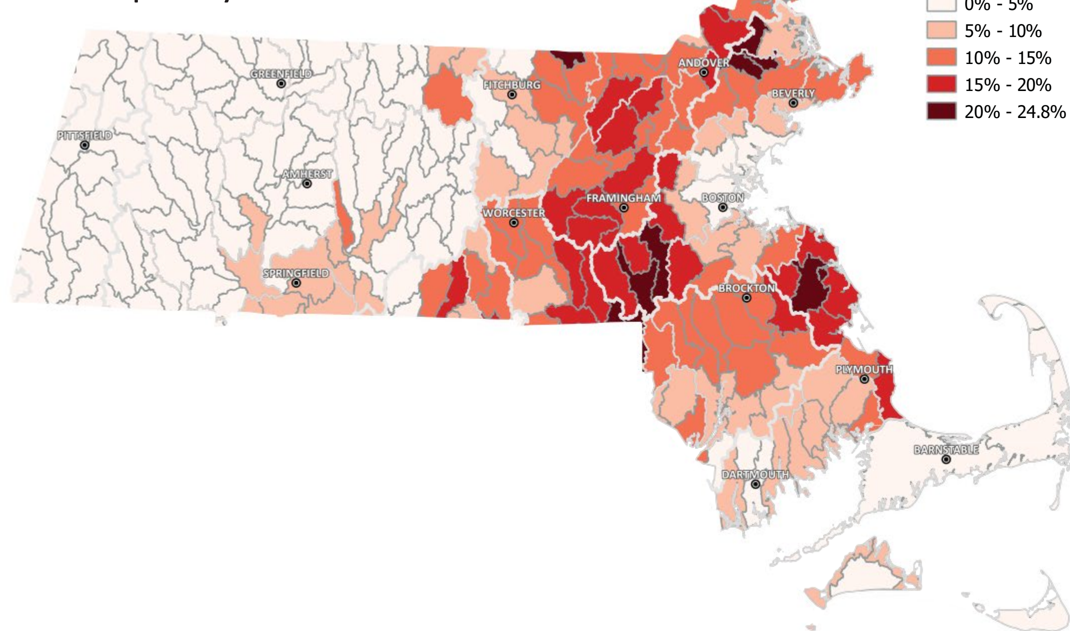
Conversion of natural and working lands to buildings, parking lots, roadways, and their associated open spaces reduces soil functions. This is because in the development process, trees and other vegetation (and their symbiotic relationship with soil biota) are upended; soil is stockpiled, compacted, or trucked away; topography, hydrology, and microclimates are altered and simplified; habitat complexity and biodiversity is reduced, and soil organic carbon rapidly oxidizes into the atmosphere.

These losses of soil function are greatest when soils are removed or drastically altered to achieve the specifications required to support the durable roads and stable buildings that make up the majority of the impervious land cover. However, to save time and money by making site development easier, conventional construction practices disturb areas well outside the building envelope and leave thin and highly compacted soils with little soil carbon or structure where it is most needed to redeem the loss of function from the impervious surfaces. To establish and maintain healthy turf or other landscaping on these degraded soils often requires on-going frequent and intensive management to provide the water and nutrients that might otherwise be provided by deeper, healthy soils.

Over 300,000 acres of the Commonwealth are expected to be newly developed by 2060 (**Map 3.1**), and an additional 60,000 acres of already developed land is likely to be redeveloped.

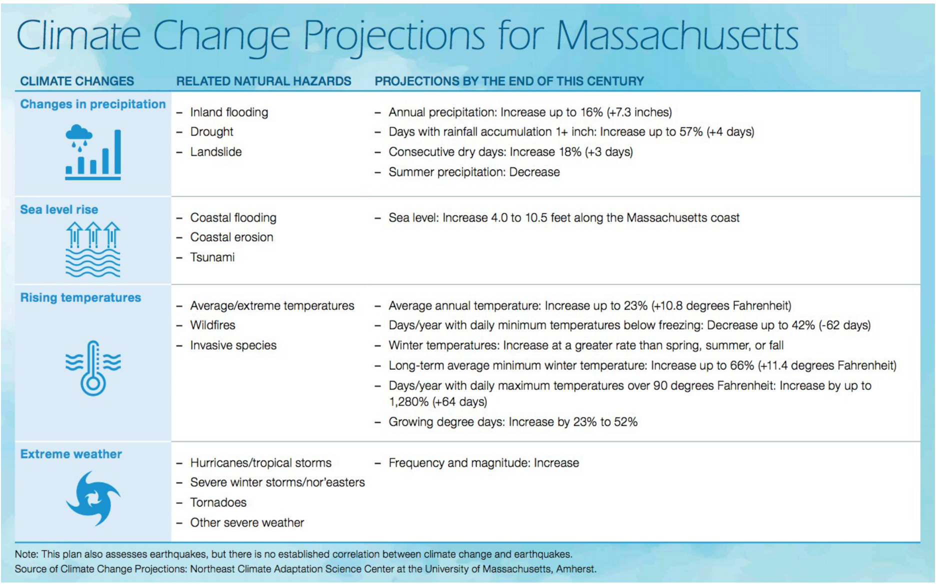
With strategic planning and action, improved development processes, and better management of developed lands there is great potential to protect and regenerate soil health as this occurs. To realize this potential and to ensure that these landscapes can be home to healthy soils that support biodiversity, infiltrate and filter stormwater, sequester carbon, and contribute to healthy communities, a coordinated and multi-pronged approach at multiple levels of government and at multiple scales of action will be required.

Map 3.1 - Development by Watershed



This must begin with accelerating smart-growth planning and conservation efforts to protect existing soil health by aiming to avoid the conversion of natural and working lands. Developing soil- smart development practices, increasing the use of green stormwater infrastructure, and improving specifications for engineered soils is an essential set of integrated actions that can replicate some of the loss of soil function when and where development occurs. Achieving widespread adoption of better turf management practices (**Figure 3.2)** is the most powerful strategy for increasing annual soil carbon sequestration in the Commonwealth.

Figure 3.1 - Climate Change Projections for MA



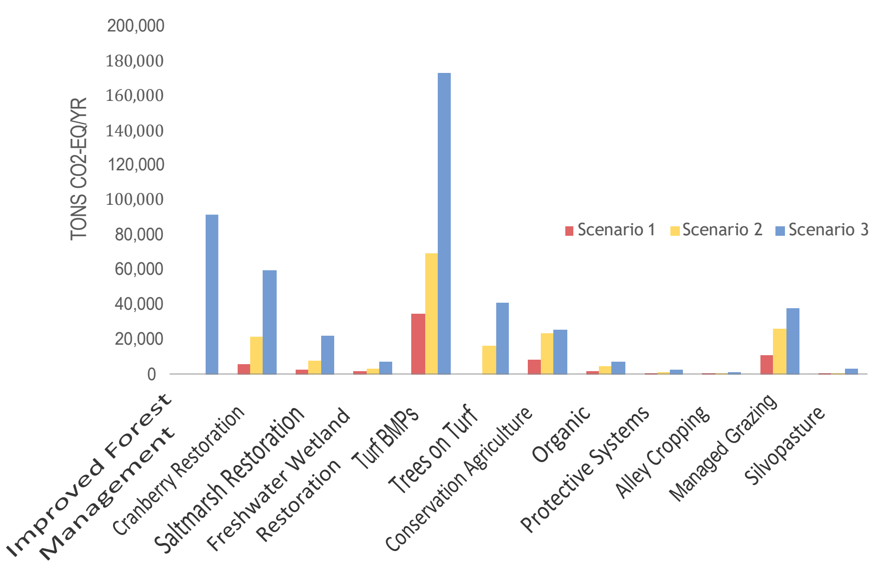
Climate Change Projections for Massachusetts

CLIMATE CHANGES	RELATED NATURAL HAZARDS	PROJECTIONS BY THE END OF THIS CENTURY
Changes in precipitation	– Inland flooding – Drought – Landslide	– Annual precipitation: Increase up to 16% (+7.3 inches) – Days with rainfall accumulation 1+ inch: Increase up to 57% (+4 days) – Consecutive dry days: Increase 18% (+3 days) – Summer precipitation: Decrease
Sea level rise	– Coastal flooding – Coastal erosion – Tsunami	– Sea level: Increase 4.0 to 10.5 feet along the Massachusetts coast
Rising temperatures	– Average/extreme temperatures – Wildfires – Invasive species	– Average annual temperature: Increase up to 23% (+10.8 degrees Fahrenheit) – Days/year with daily minimum temperatures below freezing: Decrease up to 42% (-62 days) – Winter temperatures: Increase at a greater rate than spring, summer, or fall – Long-term average minimum winter temperature: Increase up to 66% (+11.4 degrees Fahrenheit) – Days/year with daily maximum temperatures over 90 degrees Fahrenheit: Increase by up to 1,280% (+64 days) – Growing degree days: Increase by 23% to 52%
Extreme weather	– Hurricanes/tropical storms – Severe winter storms/nor'easters – Tornadoes – Other severe weather	– Frequency and magnitude: Increase

Note: This plan also assesses earthquakes, but there is no established correlation between climate change and earthquakes.
Source of Climate Change Projections: Northeast Climate Adaptation Science Center at the University of Massachusetts, Amherst.

Image from 2018 Massachusetts Integrated State Hazard Mitigation and Climate Adaptation Plan

Figure 3.2 - Comparison of Impacts of BMPs on Annual SOC Sequestration in 2050



Regreening Empty Parking Lots for Improved Soil Health

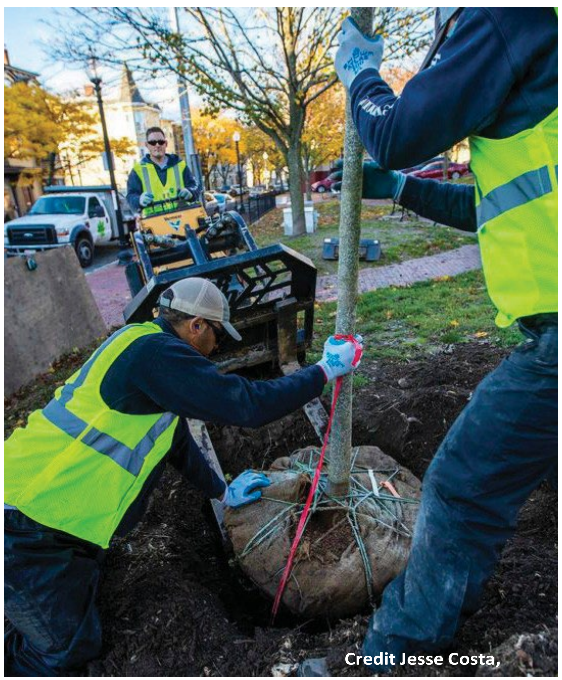
In most urban areas of Massachusetts there are many acres of under-utilized or abandoned paved parking areas that could be used for housing or other development or repurposed into trees and green space that can not only regenerate soil health, but also improve the climate resilience and water quality of urban watersheds. By prioritizing environmental justice neighborhoods, where impervious surfaces constitute 105,000 acres or 29% of the area, this regeneration of soil health can have powerful and overdue cooling and aesthetic benefits as well.

An analysis of the 64 acre Eastfield Mall property in Springfield provides an example of the opportunities. This analysis was conducted by the Regenerative Design Group as part of a broader study for the purpose of demonstrating the cost benefits of reclaiming unused or underutilized paved areas. At 89% impervious, this site contributes large quantities of stormwater to the surrounding stream complex.
Through the conversion of 2-acres of impervious soil to forest within the 100-yr buffer zone, an additional 40,000 gallons of water could be infiltrated and contribute to building up to 66-tons of soil organic carbon over time. By implementing these and other re-greening strategies across the city and the Commonwealth as described in recommendation ID-3 of this section, thousands of tons of carbon and millions of gallons of water could be stored in the soils to feed ecosystems that touch millions of lives.

To realize this change, cities like Springfield could enact a 100 foot buffer area around defined flood areas, wetlands, and water bodies and require specific ecosystem performance from those buffer zones. An incentive program or program of payments for ecosystem services (like water management and carbon sequestration) could strongly encourage conversion of paved area to trees. In this case, conversion of the buffer area would change around 5 % of the paved area of the mall property. Converting 5% of similar properties across the City of Springfield could result in up to 50 areas of new forest land.

The Impact of Development on Water Quality

Soils and the plants they support play a vital role in the hydrological cycle by intercepting, slowing, absorbing and filtering rainwater. Impervious surfaces and poorly functioning soils further impacted by development significantly reduce these ecosystem functions where they are needed to help mitigate floods and reduce non-point source pollution to our rivers and streams. According to the National Oceanic and Atmospheric Administration (NOAA), "sensitive streams can be impacted by as little as 5 to 10 percent impervious surface area [in


Credit Jesse Costa,

their watersheds], with greater impairments expected when rates exceed 20 to 25 percent." From a watershed perspective, 40% tree cover is recommended in developed areas to offset the negative impacts of developed land cover on watershed health (NOAA Online Water Quality Indicator). Twenty-four of Massachusetts' 247 subwatersheds have 20% or greater impervious cover and less than 40% tree cover (see Map 3.4 - Impervious-Dominated Land Cover by Watershed on page 97).

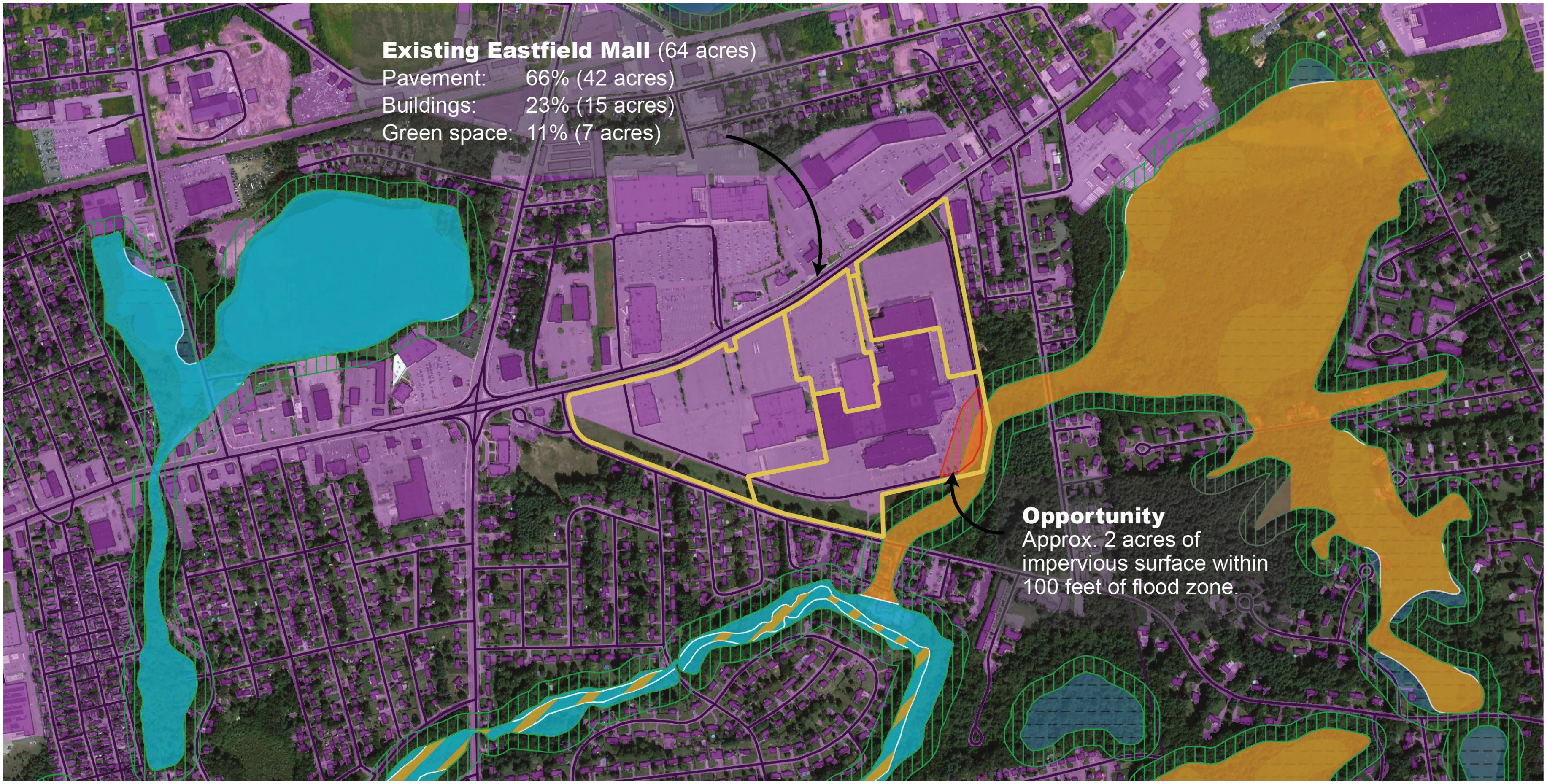
Trees in Developed Landscapes

Trees provide immense value to developed open space, providing ecosystem services that are especially important in and around urban areas. When trees are present in lawns and turf, SOC content is 20% higher than in turf alone, according to the literature review conducted for this report. As described elsewhere in this report, soils with greater SOC concentrations function at a higher level, especially when it comes to stormwater management and water quality. A Maryland review, for example, identified an increase in water infiltration of 39% and pollution reduction of 26% (Mawhorter, 2016) with trees and turf combined compared to turf alone.

Though there is little evidence that trees improve soil health in impervious areas when planted nearby, they can help mitigate and replicate some of the lost soil function. In areas dominated by impervious land cover, not only can trees enhance SOC, they also have watershed benefits, even when adopted at small scales. In urban and suburban areas, a single deciduous street tree can prevent between 500 and 760 gallons of stormwater per year from becoming runoff; a mature evergreen street tree can intercept more than 4,000 gallons over the same time period (Cotrone, 2015).

Watershed health is improved because rainwater is captured in the leaves and branches overhanging the impervious surface resulting in a direct 7% reduction in runoff and high indirect benefits downstream (Mawhorter, 2016). Ecosystem productivity is increased because photosynthesis occurs. Carbon is captured resulting in the increase of SOC in adjacent soils. And evapotranspiration of water from the adjacent soils results in soil water regulation and cooling of the area. It is conceivable that a tree in a 100 square foot area of healthy soil could have beneficial influence over 10 times that area.

The improvements to soil health through greater carbon sequestration and the attendant water performance point toward protecting and increasing tree cover in developed open space and impervious dominated areas.
In order for trees to thrive in these areas where development processes have created inhospitable conditions for plants, direct interventions to first improve or even engineer soil health may be necessary.



0 500 1000 ft

IMPERVIOUS SURFACE REFORESTATION OPPORTUNITIES

Case Study: Eastfield Mall, Springfield MA

data sources: MassGIS (MassDEP Hydrography, Impervious Surface 2005, Building Structures, Standardized Assessors' Parcels), 2010 U.S. Census (TIGER Roads), FEMA National Flood Hazard Layer, Google Satellite Imagery.

LINNEAN SOLUTIONS

IMPERVIOUS SURFACES

- brick, asphalt, concrete
- buildings
- roads

FLOOD ZONES

- 1% chance annual flood
- 0.2% chance annual flood
- floodway

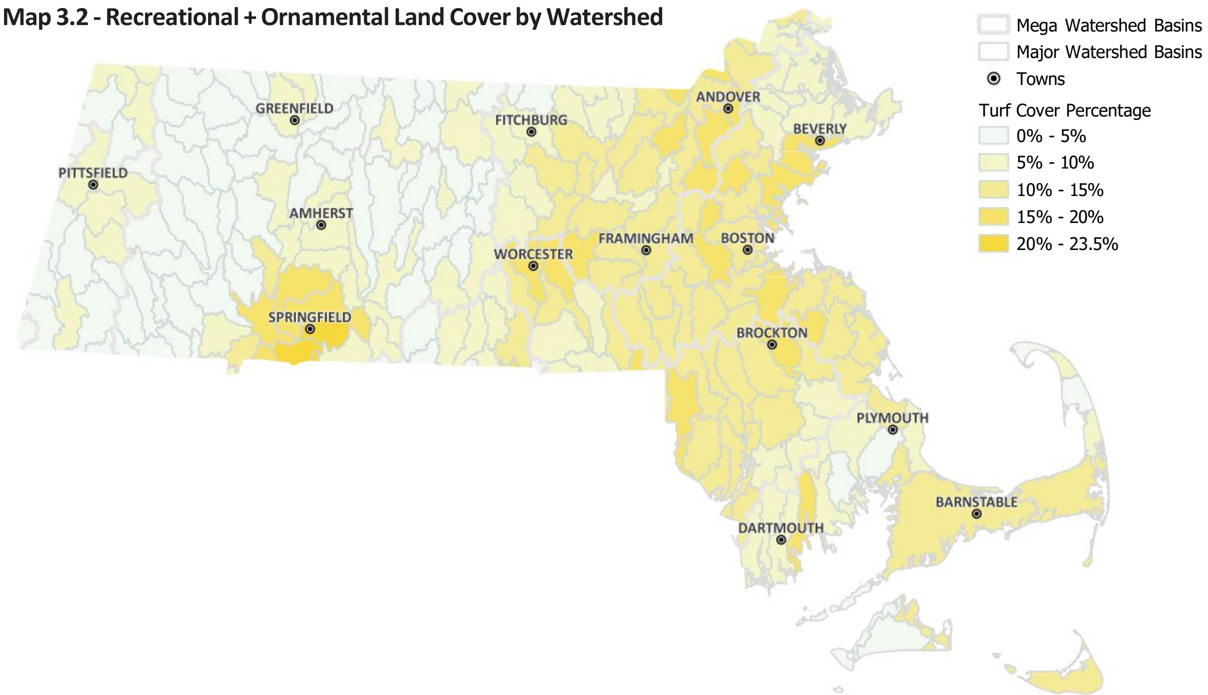
HYDROGRAPHY

- lakes, ponds, rivers
- wetlands
- 100 ft buffer around waterbodies, wetlands, and flood zones

Recreational + Ornamental Landscapes

Recreational and Ornamental Landscapes cover 438,438 acres in Massachusetts*. Here we find the lawns, gardens, and landscaping found in and around cities, residential areas, commercial and institutional campuses, parks, and golf courses. These landscapes exhibit a wide range of aesthetics, plant diversity, and management regimes, and tend to receive frequent management and inputs. These inputs contribute to a relatively high soil carbon stock, estimated at 17.6 million tons of carbon, equal to 64.7 million tons of carbon dioxide. While the fertilizers and herbicides used in these landscapes can boost carbon sequestration, runoff and nutrient transport from over-application can negatively impact water resources (Bachman et al, 2016). Encouraging wider adoption of turf best management practices is one of the most powerful ways to increase carbon sequestration rates and enhance water quality.*

Map 3.2 - Recreational + Ornamental Land Cover by Watershed



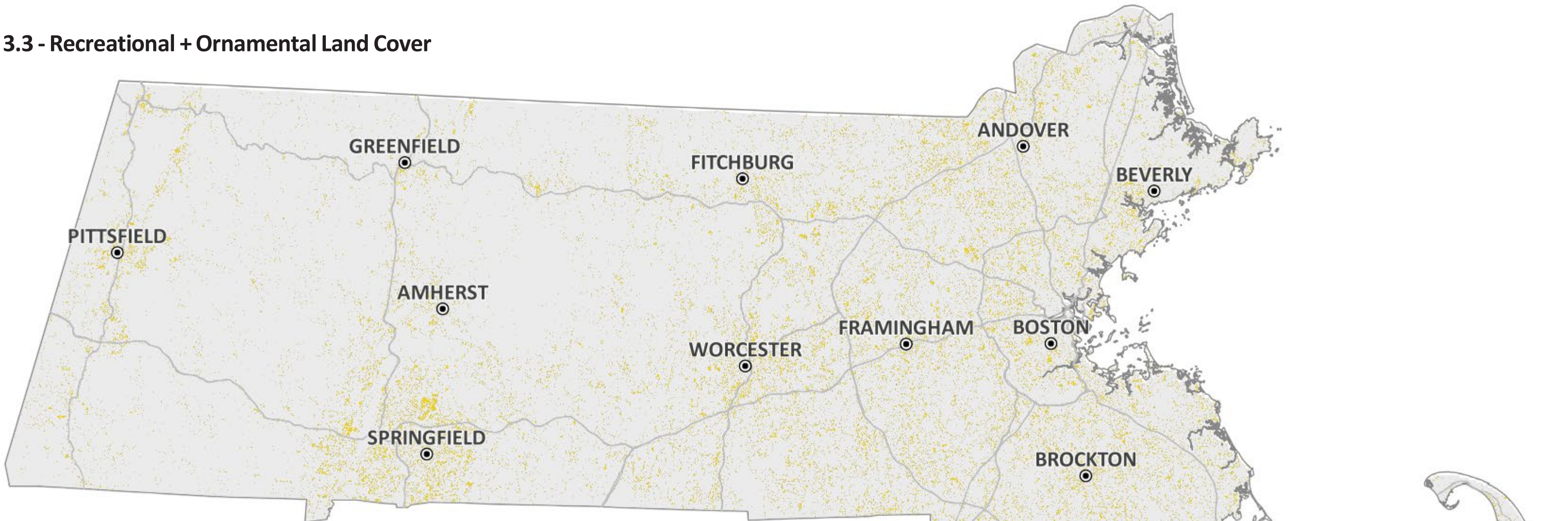
Patterns and Characteristics

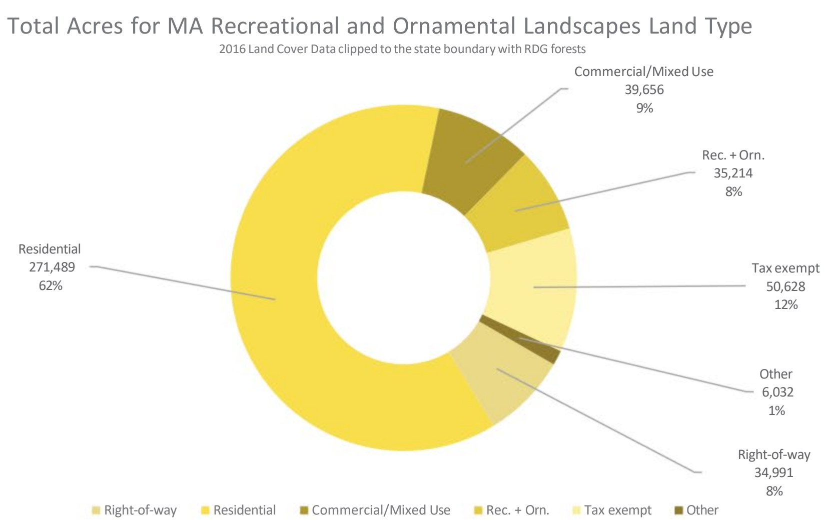
Recreational and Ornamental Landscapes typically result from the conversion of forests, farms, and other greenspace to low and medium density residential landscapes and commercial/mixed use development. Well over half of this land cover—62%, or 271,000 acres—are on parcels classified as residential.

The construction processes associated with this type of land conversion remove carbon sequestering vegetation, alter the drainage dynamics of the native soil by simplifying topography, and strip the O and A, and sometimes the B, soil horizons. Soil stockpiling practices contribute to anaerobic conditions that decrease the abundance and diversity of soil biology, further degrading the soil. If stockpiles are added back to the site, the result is a poor quality fill, and a thin layer of microbially vacant A-horizon directly on top of a highly compacted mineral soil.

The resulting soil conditions limit the depth to which plant roots can travel, compromising water infiltration and storage capacity, and the depth of carbon sequestration. These conditions can limit landscape performance for decades or longer and require higher inputs of fertilizer, water, and other labor to sustain a functional landscape. This lack of quality soil management

Map 3.3 - Recreational + Ornamental Land Cover





during development was repeatedly expressed as a challenge by turf managers at HSAP listening sessions.

According to the New England Land Futures (NELF) project, this kind of development has the potential to add 300,000 acres in Massachusetts by 2060. Therefore, any improvements made to the design, construction, and maintenance of landscapes associated with such development could have a significant impact on soil health and the services such soils provide. A 2019 study comparing soil carbon pools on sites that shared "legacies prior to development" along a gradient of yard-field-forest reinforces the importance of minimizing disturbance at the outset rather than relying on good management afterward. The study concluded that, "yard management following development disturbance can aid in soil ecosystem recovery" but results "suggest this is an incremental effect apparent only in centuries-old yards that in recent decades were mown monthly to bimonthly with clippings left on the lawn" (Peach et al, 2019, p.12).


Fowler Clark Epstein Urban Farm, Mattapan MA - Photo Credit Regenerative Design Group

Vulnerabilities

Land Conversion

The carbon loss associated with redevelopment or intensification of development on previously developed sites is far lower than that associated with development of natural and working lands. However, there are unique factors to consider. In the majority of NELF scenarios, about 8% (34,000 acres) of recreational and ornamental landscapes are likely to be converted to higher density development, i.e. impervious landscapes.

Once converted to impervious, there is lost potential for these landscapes to contribute to carbon drawdown, water quality, and other ecological functions. Approximately 206,000 acres of the Commonwealth's recreational and ornamental landscapes has agriculturally significant soils, with 98,000 of those being Prime Farmland soils. Urban, peri-urban, and suburban farms are multi-benefit agricultural entities providing enhanced food security, agricultural and soils education, and greenspace. While protecting forests, wetlands, and farmland necessitates targeting new development toward already-developed land, further study is warranted to determine how high-value soils in developed landscapes might be protected from additional development or directed toward development that increases soil health.

Climate Change + Natural Hazards

The 2020 State Forest Action Plan notes that "climate change is already exacerbating natural hazards and extreme weather events, as well as leading to new impacts that will affect the Commonwealth" (pg. 44). Like in forests, these changes including increases in the intensity and frequency of extreme heat and drought, are likely to have negative impacts on the soils of recreational and ornamental landscapes both directly and on the plants that define these land covers. Increased winter temperatures, for example, appear to prolong the metabolic season of soil biota, allowing for the breakdown of soil carbon stocks (DeAngelis, 2019). Expected increases in drought and extreme heat reduces efficiency of photosynthesis in plants while increasing their susceptibility to pests and disease (Kujawski, 2011). These factors not only decrease the carbon sequestration potential of these landscapes, but cause them to emit more carbon and decrease their water holding capacity. These losses in carbon and water holding capacity can diminish the nutrient holding capacity of soils, accelerating the general degradation of the plant and soil life resilience, resulting in a negative flywheel effect on soil health. Increased inputs of seed, fertilizer, pesticides, and physical maintenance may be necessary to mitigate these effects, but can contribute to increased carbon emissions and water quality impacts if used incorrectly.

Soils in recreational and ornamental landscapes are also at risk of increased erosion and contamination through riverine and saltwater flooding. There are currently over 15,000 acres in this land cover class located in 100-year flood zones vulnerable to floods brought on by increased frequency and magnitude of precipitation. An additional 1,900 acres of recreational and ornamental landscapes are shown to be subject to saltwater flooding with a 3-ft sea level rise. As soils become saturated, many more acres may be impacted by temporary local ponding.

Preserving and enhancing the physical structure and carbon stores of soil can help mitigate these vulnerabilities. Soils with an abundance of macropores and higher organic matter levels increase infiltration, pollutant filtration, and soil water storage capacity resulting in less flooding in all downstream land uses (Frankenberger, 2020).

Soil + Land Management

Recreational and ornamental landscapes have some of the most managed soils in the Commonwealth. A review of the scientific literature regarding carbon sequestration in turf shows that under best management practices, the grass-dominated landscapes of residential lawns, golf courses, and campuses have an

Low-mow landscape with a native grass rain garden at RiverMills Center, Chicopee MA - Photo Credit Regenerative Design Group impressive potential to improve structure and organic matter content (Kumar et al, 2016, Selhorst & Lal, 2012, Qian and Follett, 2009). Anecdotal evidence suggests other landscaped areas like perennial gardens, shrub borders, and park lands have similar potential.

However, poor management can limit or reverse gains to soil health. Little data is available about what proportion of individuals are using best management practices. According to 2016 land use data, 52.8% of all lands in this category are classified as single family residential, the majority of which are managed by homeowners or amateur landscapers.

Multiple professionals consulted through listening sessions and interviews noted the poor soil quality inherited after development was a limiting factor of landscape performance and driver of management decisions. Despite this fact, few of these professionals reported using practices known to improve soil organic matter levels. This lack of knowledge within professional communities of practice about soil processes, functions, and soil health, especially the important role of soil organic carbon is a vulnerability multiplier to soils in this class.


Greenfield Community College Outdoor Learning Laboratory, Greenfield MA - Photo Credit Regenerative Design Group

BMP’s for soil and SOC building don’t always align with prevailing aesthetic preferences. While scientifically guided management recommendations from organizations like UMass Cooperative Extension suggest mowing turf grass at 3 to 4 inches to improve performance of both plants and soil, many professionals report clients perceived this as “too long” (Owen, 2016). Additionally, many commercially available mowers are unable to be set as high as 3”.

Other threats to soil health from poor or inadequate management include the over application of fertilizers and pest controls by homeowners and other landscape hobbyists. The use of manure or manure derived compost helps improve soil structure in gardens and lawns, but the over application can cause phosphorus pollution of surface waters.

Soil Health in Turf and Lawns

By Mary Owen, Karen Connelly, and Ted Wales, UMASS

Turf educators and researchers inform us that lawns and other areas covered by turfgrass should be maintained according to their use. For example, sports fields have soil specifications based on the needs of their sport. Home lawns and many other sites, generally, do not have clear cut soil, seed, or management protocols. Some are grass and clover, some have a mix of seed varieties, others use a seed variety deemed good, based upon location and climate conditions. Some lawns are maintained by focused homeowners, others by professional companies; some lawns just grow and are mowed. Seed companies and universities strive to develop grass seed varieties that address the demands of climate and user needs. Lawn and nursery centers selling soils can direct people to good soil mixes for their properties, though this can be expensive.

Best Management Practices provide positive directives for maintaining healthy lawns, sports fields, and golf courses. BMP documents are generally over 100 pages filled with high level science information for turfgrass professionals. Fortunately, BMP concepts can be found in standing regulations, and at umassturf.org.

Nutrient Management

Nutrient management regulations in MA do not allow for the application of nitrogen-rich compost material to lawns. This rich source of nutrients has been found to leach. Excessive nitrogen and phosphorus fertilization has the potential to leach to groundwater. In MA, industry has taken out phosphorous in synthetic lawn fertilizers except when needed in planting.

Carbon Sequestration

Years of Carbon Sequestration studies on golf courses, and more recently on home and commercial lawns and sports fields, have shown that grass, particularly when maintained, does sequester carbon. Studies have yet to be done on yards choosing other types of plant materials for their lawn areas.

What actions can homeowners take to help their lawns capture more carbon?

- Raise your mower height to the highest level.
- Test your soil to determine the needs of the grass plants.
- Leave your grass clippings on your lawn or invest in a mulching mower.
- Fertilize according to the growth needs of your grass plants. Pay attention to the size of the lawn and properly calibrate your spreader.
- Aerate your lawn to allow plants to breathe and spread.
- Petition your town to direct developers to leave good topsoil on the property being developed.
- Petition your town for development within the natural landscape setting.

Spotlight on Soil Organic Carbon

Recreational and ornamental landscapes can store impressive amounts of carbon, especially when best management practices are implemented. Ten percent of all carbon held in US lands is in
Cities, on just 2.6% of the land, much of which is in soils beneath lawns and turfgrass. For example, Boston holds 1.1 MMT of carbon, of which 74% is in soils (including forests) (Churkina 2012). Some cities even have carbon levels as high as tropical forests. Typically, lawns and turfgrass are established on bare soils, highly degraded by construction. For several decades turf sequesters carbon at a rapid rate, and then becomes saturated. Part of the secret of turf's success is the high levels of irrigation and fertilizer it often receives, post establishment. This provides optimal conditions for photosynthesis, which drives carbon sequestration. However, the majority of turf cover is not regularly irrigated and receives little to no fertilizer

Massachusetts Turf SOC

Recreational and ornamental landscapes occupy roughly 438 thousand acres in Massachusetts today, projected to increase to 458 to 479 thousand acres in 2050. At present the estimated carbon stock is 17.6 million tons of carbon, equal to 64.7 million tons of carbon dioxide. These landscapes are the fourth largest land cover in the Commonwealth and has the third highest SOC stock.

Land Use Change

These landscapes are vulnerable to further development and conversion into impervious land cover, with a resulting loss of carbon. At the same time, forests, wetlands, and agricultural land are vulnerable to conversion into developed landscapes. These land cover changes represent a loss of SOC stocks. In a business-as-usual case, HSAP predicts the creation of over 20,000 new acres of recreational and ornamental landscapes by 2050.

Protecting and Enhancing SOC in Recreational + Ornamental Landscapes

Turfgrass management. Many turfgrass management practices are known to increase SOC levels. These include setting a higher mowing height, use of mulching mowers that return clippings, applying compost (which can result in excessive phosphorus over time), and the selection of particular turf species. In general, following land grant university BMPs for turf is shown to increase SOC.

Addition of trees and shrubs. This project's meta-analysis of peer reviewed research found that turf that features woody plants show roughly 20% higher SOC stocks compared with turf alone. However, it is important to select the right woody plant species, and space them properly, as the wrong species or density can shade out turfgrass. Note that this BMP also substantially increases carbon in the aboveground biomass of woody plants, though this is not accounted for here.

BMP Adoption Scenarios

Data on the potential gains and losses in turf acreage due to development are available. However, very little is known about how widespread turf BMPs are today, or how widespread they might become in the future.

HSAP's three scenarios (**Table 3.1**) make assumptions about adoption of BMPs and land use change due to development. These are used to calculate the carbon flux from SOC in this land use.

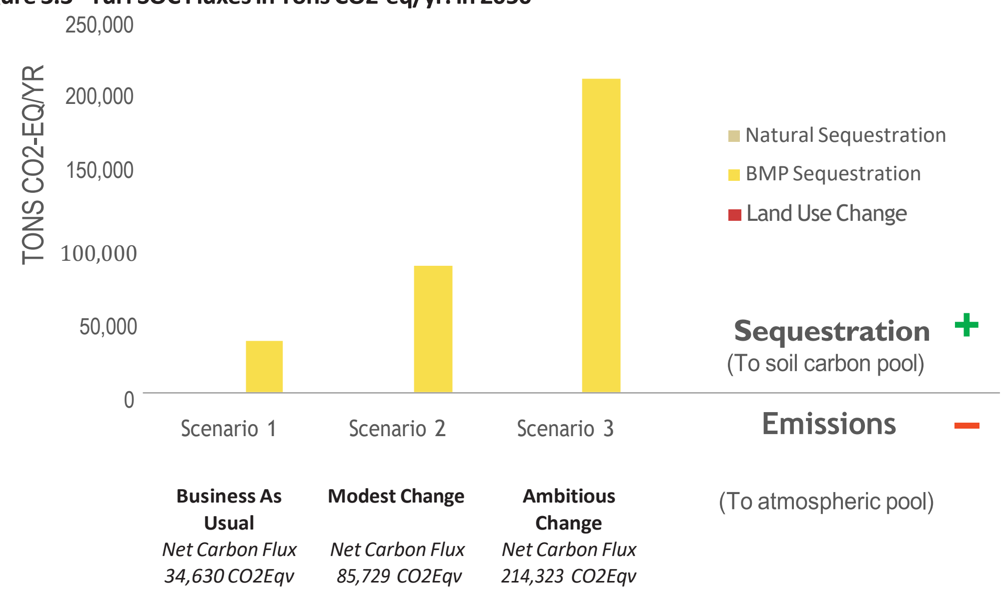
SOC Fluxes in 2050

Turf SOC net fluxes in 2050 are modest (**Figure 3.3**), ranging from 9 to 58 thousand tons of carbon or 34 to 214 tons of CO2-Eq. The most powerful impact comes from adoption of BMPs, while losses from land use change are relatively low. Improved turf management has the highest potential climate impact of any BMP modeled by HSAP.

Table 3.1 - Recreational + Ornamental Scenarios

Scenario	Adoption Assumptions	LUC Assumptions
1. Business as Usual	Adoption does not increase from current level.	100% of projected development related land conversion occurs
2. Modest Change	Turfgrass management increases from 5% to 10%. Trees are planted on 10% of currently treeless turf.	Smart growth achieves development goals, but reduces land conversion by 25%
3. Ambitious Change	Turfgrass management increases from 5% to 25%. Trees are planted on 25% of currently treeless turf.	Smart growth achieves development goals, but reduces land conversion by 50%

Figure 3.3 - Turf SOC Fluxes in Tons CO2-eq/yr. in 2050



Recommendations

Replace turf with trees and shrubs.

Recreational and Ornamental Landscapes will continue to grow in acreage across the Commonwealth. By encouraging homeowners, land managers, and developers to adopt soil smart practices with innovative programs—like 3% for 2030, 1M Tree Suburban Savannas, and Post Construction Soil Performance Standards—the health of soils can grow with them. Listening Sessions that targeted turf and landscape professionals repeatedly revealed the challenges of 'inheriting' poor soil post-development. This, combined with a perceived lack of consumer knowledge about the many benefits of healthy soils in developed landscapes, were cited as common hurdles to better practice.

That over half of this land cover is classified as single family residential (2016 LULC) should indicate the value of healthy soils programs for homeowners and land care professionals. Planting trees in and around lawns and other ornamental landscapes is one of the most powerful ways to improve the water, carbon, and cooling dynamics of urban and suburban areas

Land Conversion

R1- Increase perennial, shrub, and tree cover and diversity in recreational and ornamental landscapes where not precluded by functional requirements to increase soil functions.

a. Seek to expand funding and technical support for tree planting programs, especially on ornamental lawns and roadside grassed areas.

b. 1-Millon Tree Mass Savannas Program: Encourage 25% canopy cover over ornamental lawns, gardens, and paved areas across the State.

c. State incentives, municipal tree planting programs, and/or community nurseries could offer key support to plant 1M trees by 2050.

R2- Explore creation of comprehensive Soil Protection and Post-Construction Soil Performance Best Management Practices, with input from soil experts and stakeholders in the construction and landscaping industries. Use this BMP guidance, along with potential incentives and education/technical assistance, to protect and maximize soil health during and after site development.

a. Consider requiring a baseline soil health investigation prior to disturbance.

b. Evaluate the establishment of stockpiling and soil movement requirements or guides to limit compaction, erosion, loss of soil organic carbon stocks, and movement of harmful species or contaminants. The Soil Management Ordinance of Mahwah, New Jersey is an example of a municipal precedent.

c. Include protection for existing trees, their root zones, and other existing vegetation to maintain and expand carbon sequestration capacity for developed soils.

d. Seek to provide guidance and funding to municipal building inspectors, planning boards, and conservation commissions on adopting local soil-smart development practices and ordinances.

e. Provide training and resources to developers to help the understand and adopt soil-smart practices.

R3- Develop improved specifications for high-performance engineered soils.

Soil + Land Management

R4- Increase soil health education and outreach strategies for all professionals that play a role in the creation and maintenance of turf and ornamental landscapes

a. Support Extension and Stockbridge School to develop training and curricula for conservation agents, town planners, inspectors/regulators, and designers on the importance of soil health for the performance of projects and landscapes.

R5- Look at developing or updating statewide programs that celebrate, educate, and incentivize soil health practices in the developed landscape.

a. Seek to establish a statewide "3% by 2050" (or similar) initiative for turf and lawn managers focused on increasing soil organic matter in the top 8" of soil to 3% by 2050 using BMP's.

b. Create or support stakeholder-specific awareness-building, education, and training programs on managing turf and ornamental landscapes for soil health.

c. Consider developing a Healthy Soils Pilot Program that demonstrates successful implementation in order to exemplify healthy soil practice in developed landscapes. Focus on state and institutional facilities.

d. Explore incorporation of healthy soils practices into the MVP and CPA programs, the Wetlands Protection Act and Riverfront Protection Act, and the Massachusetts Environmental Policy Act (MEPA). For MEPA, the post-construction soil BMP's could be associated with greenhouse gas emissions policies.

R6- Direct and support managers of State lands to implement turf, lawn, and landscape management practices that improve soil health.

a. Aim to realize 100% adoption of BMP's on public lands. Guided by UMass Turf Extension and/or those identified by the Healthy Soil Pilot Programs for turf.

b. Certification of land managers in BMP's and soil health.

c. Regular soil testing and data collection. Testing guides management and produces data for ongoing research efforts on the effects of management on soil health and water quality.

d. Replace equipment to allow for BMP implementation such as high-deck and mulching mowers.

e. Establish a goal for canopy cover and enhance tree cover on state-managed lawns and ornamental landscapes to meet this goal.

R7- Facilitate development of new State and Municipal Policies that improve the management of developed open space.

a. Lawn Fertilizer Best Management Practices (BMPs): Create a work group to examine the efficacy of any existing BMPs, and the success of other programs both in Massachusetts and in other states. Develop recommendations to improve soil health and reduce nutrient runoff that may include the following:
   i. Consideration of training programs and certification for all lawn care companies and professionals.
   ii. Guidance and restrictions on type, amount, frequency, and timing of fertilizer applications.

b. Municipal Nutrient Management Bylaws: Explore mechanisms to allow municipalities to adopt and enforce local evidence-based ordinances to protect surface and groundwater quality. Consider providing a model bylaw.

c. Expand nutrient and organic waste recycling programs.

R8- Conduct and support research and development of practices to regenerate, protect, and improve soil health in developed open space:

a. Soil depth and content standards for recreational turf.

b. Impact and appropriate use of compost on new and existing turf.

c. Methods to increase stormwater infiltration, nutrient uptake, carbon sequestration, and other soil functions of existing turf.

Natural Hazards + Climate Change

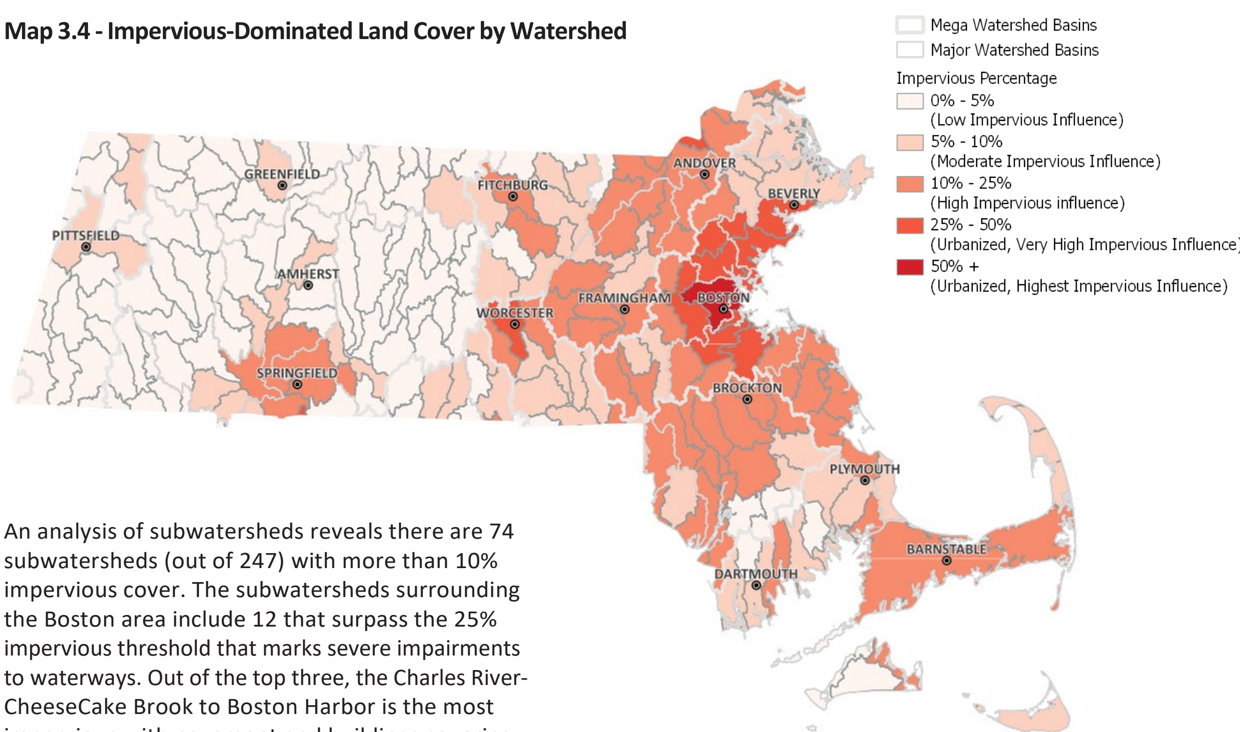
R9- Promote protection, management, and restoration strategies that increase biodiversity, ecosystem health, carbon sequestration, and water retention and infiltration on the landscape.

R10- Ensure that appropriate state offices (MVP CZM, etc.) support maintaining space for wetland migration in coastal areas, via land acquisition or other approaches.

Impervious-Dominated Landscapes

*Despite the abundance of impervious surfaces, there is little research on the function of soil below impervious surfaces. In this abbreviated section we explore some of what is known about the patterns **(Map 3.4)** and characteristics of the 475,033 acres in Massachusetts that have been altered to create buildings, parking lots, and more than 73,500 miles of roadways (MassDOT, 2019).*

Map 3.4 - Impervious-Dominated Land Cover by Watershed



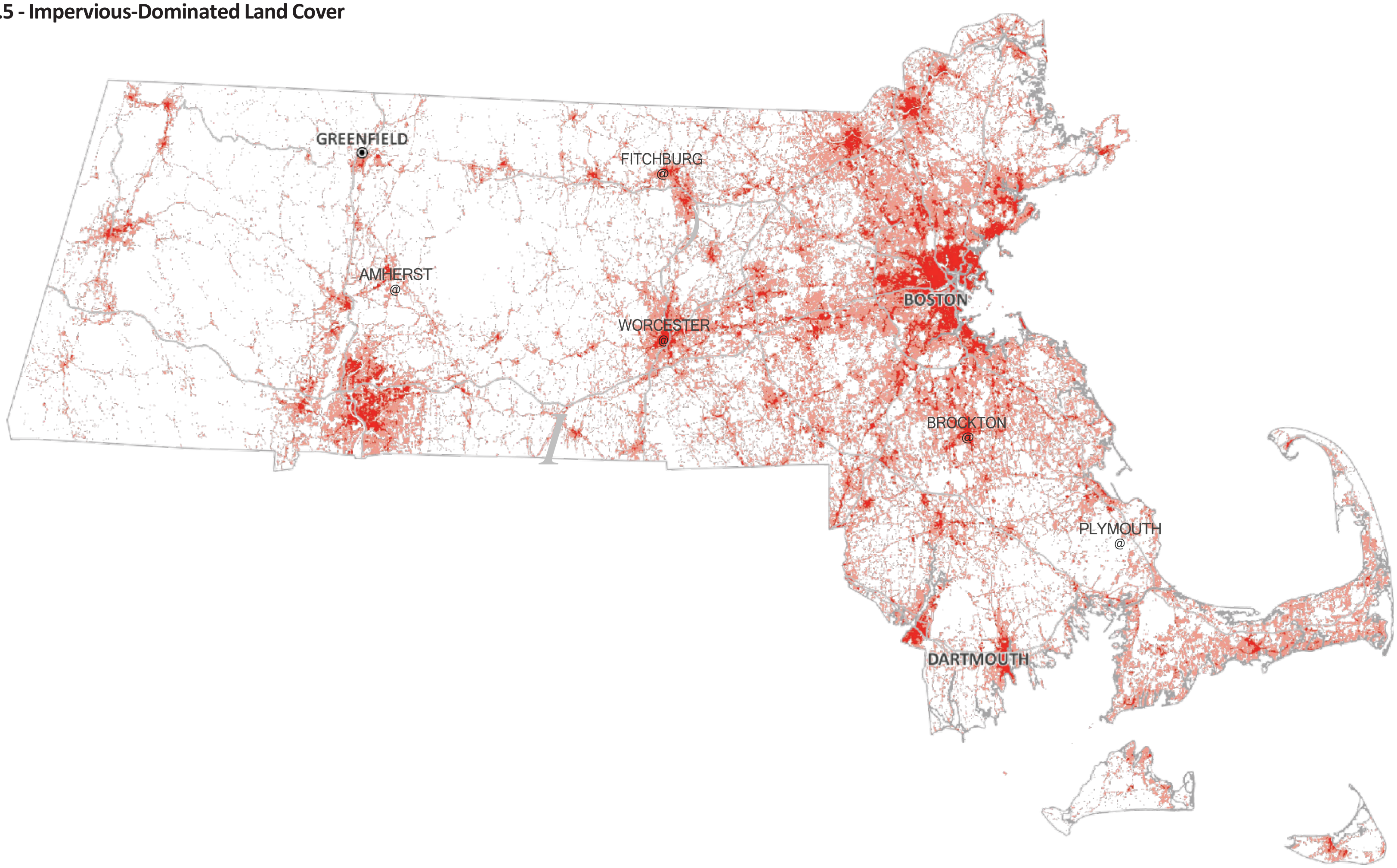
An analysis of subwatersheds reveals there are 74 subwatersheds (out of 247) with more than 10% impervious cover. The subwatersheds surrounding the Boston area include 12 that surpass the 25% impervious threshold that marks severe impairments to waterways. Out of the top three, the Charles River-CheeseCake Brook to Boston Harbor is the most impervious with pavement and buildings covering more than half of all soils.

It has been widely proven that the majority of the soil-based ecosystem services, especially those associated with soil carbon and water management, are lost once land is converted from natural or working to impervious land cover (HSAP SOC, Conservation Engineering Division- NRCS, 1986). In the Commonwealth, over 32% of this compromised land cover is on parcels designated as right-of-way (mostly roadways). Another 26% are designated as single family residential (**Map 3.5**).

It is estimated that up to 3% of all soil organic carbon in Massachusetts is currently stored in soils under impervious cover. However, the potential gains through sequestration by 2050 are virtually zero (HSAP SOC, 2020). This is largely due to the elimination of the biological processes that drive carbon sequestration and physical modifications that reduce or eliminate other soil functions. As a result, actions to limit impervious cover by following the principles of smart growth and to replicate what has been lost to paving and building construction must be made a priority.

These actions include influencing how and where impervious soils are built by directing development toward already degraded soils and using smart growth principles, as well as increasing the use of high-performance engineered base materials. Other soil-

Map 3.5 - Impervious-Dominated Land Cover



smart modifications to the construction and development processes would limit soil disturbance beyond the construction footprint and increase the use of green stormwater infrastructure.

In addition to regenerating soil function lost to development and limiting the impact of future development, addressing the risks to soil health posed by climate change and sea level rise must also be considered. Twenty-thousand acres of paved lands and buildings are at high risk of regular or permanent flooding by 2050. Responding to this threat with nature-based approaches like marsh restoration combined brownfield clean-up and managed retreat are wise climate adaptation strategies which also increase statewide soil health. These and other strategies are described more fully in the "Goals, Actions, and Strategies" section.

Patterns and Characteristics

The impervious land types of our urban and other developed areas cover some of the most frequently and most intensely modified soils in the state. The requirements for the construction of durable paved areas and stable buildings often necessitate the removal of native soils and ecosystems they support in favor of engineered soil and simplified vegetative communities. The NELF Recent Trends scenario projects that area under this land cover will increase from roughly 475 thousand acres in 2020 to 542 thousand in 2050. The Growing Global scenario has impervious cover closer to 800 thousand acres.

This quickly growing class of degraded soils are distributed widely across the Commonwealth, with concentrations around the major cities of Springfield, Worcester, and most notably in the Boston Metropolitan Statistical Area. An analysis of subwatersheds reveals there are 74 subwatersheds (out of 247) with more than 10% impervious cover. The subwatersheds surrounding the Boston area include 12 that surpass the 25% impervious threshold that marks severe impairments to waterways. Out of the top three, the Charles River-Cheese Cake Brook to Boston Harbor is the most impervious, with pavement and buildings covering more than half of all soils.

Due to many factors, forests are the most likely land type in Massachusetts to be converted to impervious cover (Thompson, 2020). It is estimated when forested soils are converted to impervious cover, they lose 33 tons or more soil organic carbon per acre (HSAP SOC Stocks and Flux, 2020) and produce a 4-to-12x increase in stormwater runoff (Bright Hub Engineering, 2020).

Massachusetts Impervious SOC

Current carbon stocks are estimated at 10.5 million metric tons, equal to 38.8 million tons of carbon dioxide. Unlike other land uses, soils under impervious cover tend to neither lose nor gain carbon, so no figure is provided to show SOC flux as there is no change during this period (except from additional impervious area added due to development; SOC losses from this development are listed under the use which is converted to impervious). Therefore, underutilized impervious land is ideal for development from a soil carbon perspective, as it has little left to lose.

Management and Soil Carbon

At present, there is little evidence that management practices influence the rate of carbon flux in soils under impervious surfaces. However, it seems likely that some of the mechanisms that drive soil carbon accumulation in ordinary soils are likely to occur in impermeable soils as well.

Given the powerful effects that trees have to ensure soil carbon sequestration in forested and grass-dominated ecosystems, the authors of this report speculate that trees planted in impervious surfaces, like typical urban street trees, may sequester some soil organic carbon.

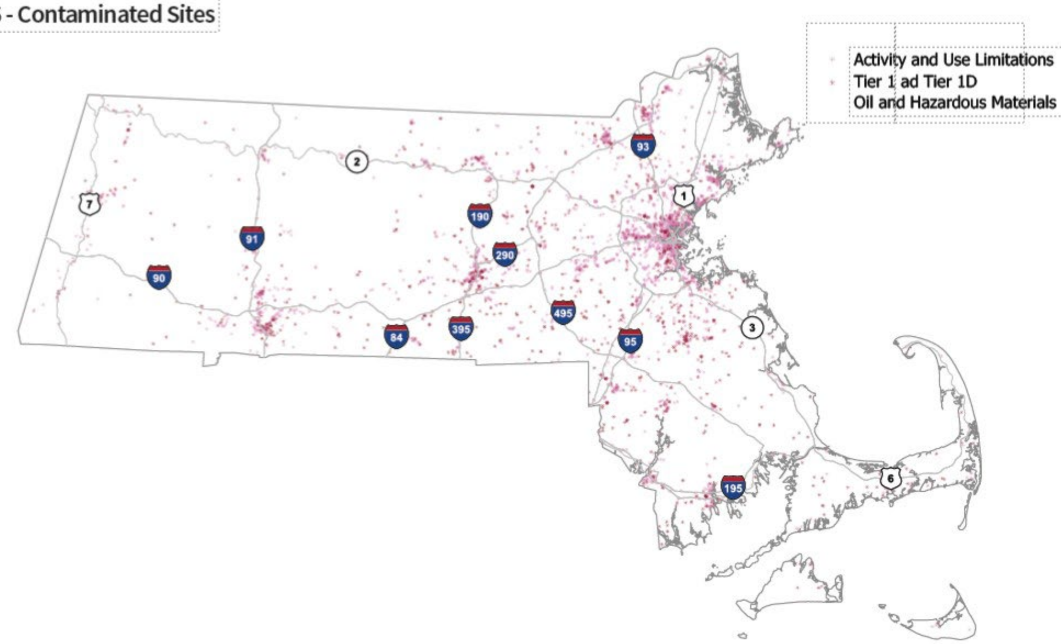
Changes and Vulnerabilities

At least four percent of impervious lands, totaling more than 18,000 acres, are located in the historic FEMA 100-year flood zone. With 3-feet of sea level rise roughly 1,400-acres of impervious and urbanized lands will be permanently inundated and almost 1,800-acres will be below this new sea-level. The projected increase of magnitude and frequency of extreme weather events along with sea-level rise predict that more developed soils will be flooded more often.

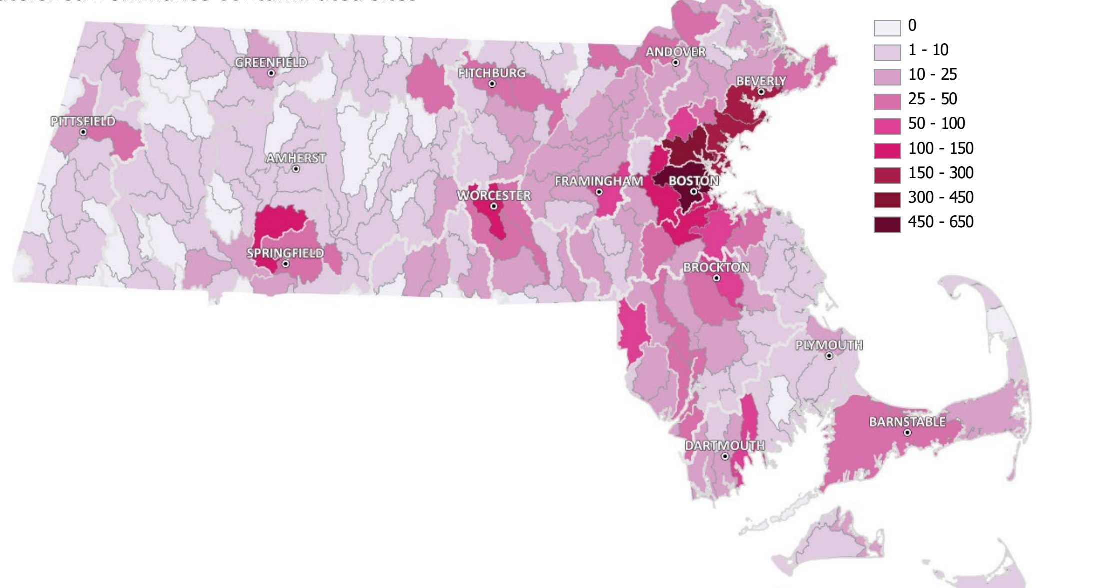
Many of the soils in and around existing impervious surfaces have been both changed structurally and contaminated by historic land uses. Persistent lead contamination in roadside soils generated from historic vehicle emissions is an example of widespread but low level contamination. **Maps 3.6 and 3.7**, generated from a list of brownfields and other contaminated sites maintained by MassDEP Brownfields, shows that our more urbanized watersheds bear the burden of contamination from industrial land uses.

The intensive remediation of chemical contamination and the systematic regeneration of soil functions is often costly, however the costs of not addressing these legacy issues are often borne most heavily by the black, brown, poor and other vulnerable populations of the Commonwealth (MA Env. Justice webpage). Redeveloping sites that can
be brought up to acceptable safety standards for housing, renewable energy production, and other developed and impervious uses is one solution to relieving development pressure from higher functioning soils.

Map 3.6 - Contaminated Sites



Map 3.7 - Watershed Dominance Contaminated Sites



Post Construction Soil Performance

One way to ensure soil health during and after the construction process is to require that vegetated soils on-site meet or exceed the performance of natural, healthy soils in the area. Of course, any Post Construction Soil Performance measures to be considered in Massachusetts will need to be developed in coordination with other state agencies and through stakeholder input, including soil experts, municipal officials, landowners, and developers. King County, Washington and the State of Vermont have developed and adopted standards focused on providing better stormwater performance by ensuring soil quality and depth.

As noted in the Vermont Stormwater Management Manual, higher quality and deeper soils provide "greater stormwater functions in the post-development landscape, provides increased treatment of pollutants and sediments that result from development, and minimizes the need for some landscaping chemicals, thus reducing pollution through prevention". In Vermont, these standards apply to "all disturbed areas within the limits of the site which are not covered by an impervious surface, incorporated into a structural stormwater treatment practice, or engineered as structural fill once development is complete" (Vermont Stormwater Management Manual, 2017). Post-construction soil performance must address several factors, including:

1. Understanding the Soil Resources of the Site.

Perform pre-construction soil testing and/or reference the NRCS Soil Survey where available. This testing should document the current or representative soil types, their texture, depth of horizon, organic matter content, and bulk density. Additionally, in urbanized or heavily disturbed soils, studying soil for contamination is essential.

2. Limiting Total Site Disturbance.

This can be achieved through:

- Preserving site topography, mature trees and their rooting zones, and other natural/existing vegetation.
- Erecting and maintaining construction fencing and other measures to limit the movement and storage of machines and materials beyond the building/project footprint.

3. Mitigating Soil Compaction.

Once the majority of construction is complete, compaction of the sub-soil must be remediated where greenspaces are to be established by either:

- Decompacting subsoil to a depth of at least 10 inches below the sub-grade surface or to bedrock, whichever is shallower.
- Restoring the soil to "The depth of the 0 and A horizons on the NRCS Official Soil Series Description of the native mapped soils", as recommending in the VT standard.

4. Specifying Soil Quality + Plantings.

The site must have a pH and nutrient profile suitable for the proposed planting plan. Plantings must be successfully established prior to final sign-off. A 2-3 year establishment period is recommended.

5. Flexibility in Achieving the Standard.

Both King County, Washington and the State of Vermont allow several different options for meeting the soil performance standards. King County's four options are shown in the table below, along with guidelines for achieving these standards in turf and planting beds. Vermont's options include:

- Option 1: Leave undisturbed native vegetation and soil and protect from compaction during construction.
- Option 2: Amend existing site topsoil or subsoil in place.
- Option 3: Remove and stockpile existing topsoil during grading, using improved stockpiling practices.
- Option 4: Import topsoil mix, or other materials for mixing, including compost, of sufficient organic content and depth (specified elsewhere).

6. Effective Enforcement.

As evidenced by the experiences of King County Solid Waste Division staff, provision of training and field evaluation materials to support inspections is often insufficient and efficacy is often dependent on available time and resources to enforce updated practices.

Summary of Soil Management Options

Soil Management Options and pH	Using Pre-approved Amendment Rates		Using Custom Amendment Rates*
	Turf	Planting Beds	Turf or planting beds
Option 1 Leave native soil undisturbed, protect from compaction.	Not applicable - Undisturbed areas do not require soil amendment.	Not applicable - Undisturbed areas do not require soil amendment.	Not applicable - Undisturbed areas do not require soil amendment.
Soils that have been cleared and graded, and not covered by impervious surfaces or developed as a storm water structure, must be restored to 8 inches deep, using one of the following three options. Visit http://your.kingcounty.gov/solidwaste/compost-calculator.htm to calculate quantities of compost and/ or topsoil needed for Options 2-4 below.			
Option 2 Amend soil in place.	Mix 1.75 inches of compost 8 inches deep.	Mix 3 inches of compost 8 inches deep.	Use online calculator*.
Option 3 Import topsoil containing adequate organic amendment.	Import 8 inches of soil mix containing approximately 75-80% sandy loam and 20-25% compost.	Import 8 inches of soil mix containing approximately 60-65% sandy loam and 35-40% compost.	Not applicable.
Option 4 Stockpile site soil, reapply, amend in place.	Reapply stockpiled soil and amend in place with 1.75 inches of compost, for a combined minimum depth of 8 inches of soil and compost.	Reapply stockpiled soil and amend in place with 3 inches of compost, for a combined minimum depth of 8 inches of soil and compost.	Use online calculator to determine amendment rate.* Reapply stockpiled soil and amend in place with a combined minimum depth of 8 inches of soil and compost.

King County Washington provides several ways to ensure Post Construction Soil Performance. To be effective in Massachusetts, flexibility combined with accountability will be essential. Custom amendment rates must be approved based on soil and amendment tests and calculations using the soil amendment calculator at http://your.kingcounty.gov/solidwaste/compost-calculator.htm.

Recommendations

Land Conversion

Limiting and reversing the extent and intensity of land conversion to impervious cover are two of the most important ways to protect soil health in Massachusetts. The recommendations below nest several actions within a three- pronged approach:

I1- Limit conversion of forests, farms, and other green open space through conservation efforts, planning initiatives, and supports for working lands:

a. Encourage higher-density in-fill development and redevelopment on impervious soils.

b. Seek to increase support for successful conservation programs and initiatives like the Chapter 61 program and the Agricultural Preservation Restriction Program, which require resources to implement.

c. Look at developing necessary programs to achieve new state goals like the No Net Loss of Forests and Farms championed by the Resilient Lands Initiative.

d. Introduce soil-based analysis and criteria into the selection process for these programs to help protect the most at-risk soil resources.

I2- Explore transformation of current development and construction processes to avoid loss of soil health.

a. Create policies to protect and enhance soil post development

   i. Ensure Post-Construction Soil Performance for open space associated with development/ redevelopment projects.

b. Improve performance specifications for engineered soils that increase the stormwater infiltration and storage capacity in and around impervious surfaces.

c. Educate developers, contractors, and landscape specifiers about preserving soil health during and after site development.

   i. Create and support continuing education and certification programs on healthy soils for all people engaged in site development including building inspectors, town planners, developers, general contractors, and equipment operators.

I3- Regreen under-used or abandoned impervious surfaces and regenerate soil health on already developed lands. Realization of the "no net loss of forests and farms" and "no net loss of soil organic carbon" goals depend on strategic conversion of unused paved landscapes to planted landscapes. This can be accomplished by:

a. Using incentives based on analysis and work with municipalities to pilot the restoration of unused and abandoned impervious surfaces like parking lots to greenspace, especially with trees, where development pressure is low and the need for green space, flood resilience, and reduced heat island effect is high. A recent analysis of parking lots in the state found about 70,000 acres of parking lots (the equivalent of 5 average sized municipalities) and showed that a portion of these lots are in flood prone or other environmentally sensitive sites,

b. Retrofitting existing highly impervious areas with green infrastructure like tree belts and rain gardens. Such restoration could be piloted on city and town-owned lands and be funded through resilience-oriented grants at the municipal level; and

c. Encouraging 25% canopy cover over ornamental lawns, gardens, and paved areas across the State.

Soil + Land Management

At present, there is little evidence that typical management practices for existing impervious surfaces significantly impact the function of underlying soils. As noted repeatedly in this report, soils subjected to conventional construction practices and sealed under an impervious surface have lost much structure and function of healthy soils. The functions they retain appear to be relatively stable, regardless of surface management.

However, there are some physical modifications to existing streetscapes, parking lots, and other impervious areas that could regenerate some of the lost soil functions, especially stormwater infiltration and biofiltration. Permeable pavements, the addition of street trees, and green infrastructure such as rain gardens, have been promoted by watershed advocates and designers for their contributions to restoring healthier soil-water dynamics.

While there is strong evidence that street trees sequester carbon in their aboveground biomass, it appears that the impacts on soils under impervious surfaces have not been studied.

This should be a research priority, and, if desirable impact on carbon in soils under impervious cover is found, tree planting in streets and parking lots could provide a lever to increase carbon storage.

The authors of this plan found little documentation about additional degradation to soils and the services they provide from the management of existing impervious surfaces. Given that impervious soils are commonly used for transportation and industrial purposes, better understanding the impacts of these uses on soils and ways to limit contamination also seems critical.

Lastly, covering soils known to be contaminated with impervious surfaces has been a long-used strategy. Maintaining these surfaces in good condition to prevent contaminated soils from being exposed to water, air, animals, and people is essential to protect human and environmental health.

I4- Accelerate retrofitting of suitable impervious surfaces with stormwater recharge features and street trees to regenerate lost soil-water function

I5- Seek to provide technical and financial support to managers of larger and moderate impervious areas to establish and maintain green infrastructure.

I6- Support the development of Impervious + Urban Soils Research Programs:

a. Study impact of urban street trees and green infrastructure on soil organic carbon accumulation and other functions.
b. Study impact of typical management practices on underlying soil resources.

Natural Hazards + Climate Change

The losses of soil function associated with conversion to impervious surfaces exacerbate many of the flood, sea-level-rise, extreme temperature, and drought risks associated with climate change detailed in the Massachusetts State Hazard Mitigation and Climate Adaptation Plan. Preventing the conversion of healthy soils, especially in flood prone, coastal, and urban areas, to impervious conditions is essential to limit increased vulnerability. Many of the existing risks can be mitigated by regenerating or replicating the lost soil function in and around impervious areas.

Much of this work is more easily done on other landcovers and following the recommendations described for wetlands, forests, agriculture, and developed open space will have beneficial effects on intensively developed areas and impervious soils.

Enhancing the ability of impervious soils to store and filter higher amounts of rain water from increases in precipitation and increasing the tree cover over impervious areas are two strategies that can be employed both as effective retrofits to existing areas and in new development.

I7- Promote proactive efforts to enhance soil-based resistance and resilience capacity to climate and natural disturbances in and around developed areas.

a. Develop watershed resilience plans for subwatersheds already significantly impacted by impervious cover or at high risk of future development to protect or regenerate soil function.
b. Explore integrating green infrastructure and other nature-based solutions into development and redevelopment projects to mitigate or regenerate loss of soil function due to development process and increase in impervious surfaces.


Hitchcock Center - Photo Courtesy of Jim Newman

Developed Lands References

2017 Vermont Stormwater Management Manual Rule and Design Guidance. Vermont Agency of Natural Resources. Accessed on June 10, 2019 from https://dec.vermont.gov/sites/dec/files/wsm/stormwater/docs/Permitinformation/2017%20VSMM_Rule_and_Design_Guidance_04172017.pdf

Bachman, Matthew & Inamdar, Shreeram & Barton, Sue & Duke, Joshua & Tallamy, Doug & Bruck, Jules. 2016. A Comparative Assessment of Runoff Nitrogen from Turf, Forest, Meadow, and Mixed Landuse Watersheds. JAWRA Journal of the American Water Resources Association. 52. n/a-n/a. 10.1111/1752-1688.12395.

Bright Hub Engineering. 'Rational Method Runoff Coefficient Tables for Storm Water Runoff Calculation'. Accessed June 25, 2020. https://www.brighthubengineering.com/hydraulics-civil-engineering/93173-runoff-coefficients-for-use-in-rational-method-calculations/

Churkina G. (2012) "Carbon cycle of urban ecosystems" in Lal, R and Augustin, B (eds) Carbon Sequestration in Urban Ecosystems Dordrecht, Springer

Conservation Engineering Division -- Natural Resources Conservation Service. "Urban Hydrology for Small Watersheds, TR-55. 210-VI-TR-55, Second Ed.". 1986. United States Department of Agriculture.
https://www.researchgate.net/publication/290190158_Soil_in_the_City_Sustainably_Improving_Urban_Soils

Cotrone, Vincent. "The Role of Trees and Forests in Healthy Watersheds." Penn State Extension, August 17, 2015. https://extension.psu.edu/the-role-of-trees-and-forests-in-healthy-watersheds.

Frankenberger, Jane. "Land Use & Water Quality." Accessed July 6, 2020. https://engineering.purdue.edu/SafeWater/watershed/landuse.html.

Kujawsk, Ron. (2011). Long-term Drought Effects on Trees and Shrubs. University of Massachusetts Cooperative Extension. Accessed August 2020 from https://ag.umass.edu/landscape/fact-sheets/long-term-drought-effects-on-trees-shrubs

Kumar, Kuldip & Hundal, Lakhwinder. (2016). Soil in the City: Sustainably Improving Urban Soils. Journal of Environmental Quality. 45. 2-8. 10.2134/jeq2015.11.0589.

MassDOT. (2019). Massachusetts Road Inventory Year-end Report- 2018. Massachusetts Department of Transportation. Accessed on May 28, 2020 from https://www.mass.gov/files/documents/2019/03/27/2018-ri-ye-final.pdf
New England Land Futures

Mawhorter, Julie. (2016). Tree Canopy Land Use Loading Rates in the Phase 6 Watershed Model- Chesapeake Bay Partnership review of proposed methodology. Presentation- February 11, 2016. Accessed on August 14, 2020 from https://www.chesapeakebay.net/channel_files/23466/webinar_tree_canopy_land_use_loading_rates_final_11feb2016.pdf

National Oceanic and Atmospheric Administration (NOAA). How To Use Land Cover Data as a Water Quality Indicator, Online Tool. https://coast.noaa.gov/howto/water-quality.html

Owen, Mary C, and Jason D Lanier. 2016. "Best Management Practices for Lawn and Landscape Turf, Version 1.51", UMass Extension Turf Program.

Peach, Morgan E., Laura A. Ogden, Eleni A. Mora, and Andrew J. Friedland. 2019. "Building Houses and Managing Lawns Could Limit Yard Soil Carbon for Centuries." Carbon Balance and Management 14 (1): 9. https://doi.org/10.1186/s13021-019-0124-x

Qian, Y.L., Follett,R.F., Assessing Soil Carbon Sequestration In Turfgrass Systems Using Long-term Soil Testing Data, Agronomy Journal, 2002. 94:930-935.

Raciti, S. M., L. R. Hutyra, and A. C. Finzi. (2012). Depleted soil carbon and nitrogen pools beneath impervious surfaces. Environmental Pollution 164:248–251.

Raciti, Steve & Hutyra, Lucy & Rao, Preeti & Finzi, Adrien. (2012). Inconsistent definitions of "urban" result in different conclusions about the size of urban carbon and nitrogen stocks. Ecological applications : a publication of the Ecological Society of America. 22. 1015-35. 10.2307/23213935.

Raver, Anne. "The Grass Is Greener at Harvard." The New York Times, September 23, 2009. Accessed June 2020. https://www.nytimes.com/2009/09/24/garden/24garden.html?auth=link-dismiss-google1tap&pagewanted=2

Selhorst, Adam & Lal, Rattan. (2012). Net Carbon Sequestration Potential and Emissions in Home Lawn Turfgrasses of the United States. Environmental management. 51. 10.1007/s00267-012-9967-6.

Thompson, Jonathan, Fallon Lambert, Kathy, Foster, David. 2017. Changes to the Land: Four Scenarios for the Future of the Massachusetts Landscape. Harvard Forest.

Thompson, Jonathan. Land Consumption Modeling, Landis II.

Travaglini, Mary. 2020. "Environmental Benefits of Organic Lawns". Accessed on June 30, 2020 from:https://www.ecolandscaping.org/03/installing-and-maintaining-landscapes/lawn-care/environmental-benefits-of-organic-lawns/

Zirkle, Gina & Lal, Rattan & Augustin, Bruce. (2011). Modeling Carbon Sequestration in Home Lawns. HortScience. 46. 808-814. 10.21273/HORTSCI.46.5.808.

'Municipal Healthy Soils Fact Sheet' - draft by Andrew Brousseau

Harvard University Organic Maintenance Program. Accessed June 2020. https://www.energyandfacilities.harvard.edu/facilities-services/landscape-maintenance/organic-maintenance-program

04 | Conclusions

Conclusions

The findings and recommendations of this Action Plan are intended to empower people to protect and enhance the soil resources that support thriving ecosystems and human communities of the Commonwealth. Like the ecosystems they support, soils are diverse. Their characteristics, along with their capacity to provide services like stormwater infiltration and nutrient availability, vary widely. This variation depends both on inherent and dynamic properties.

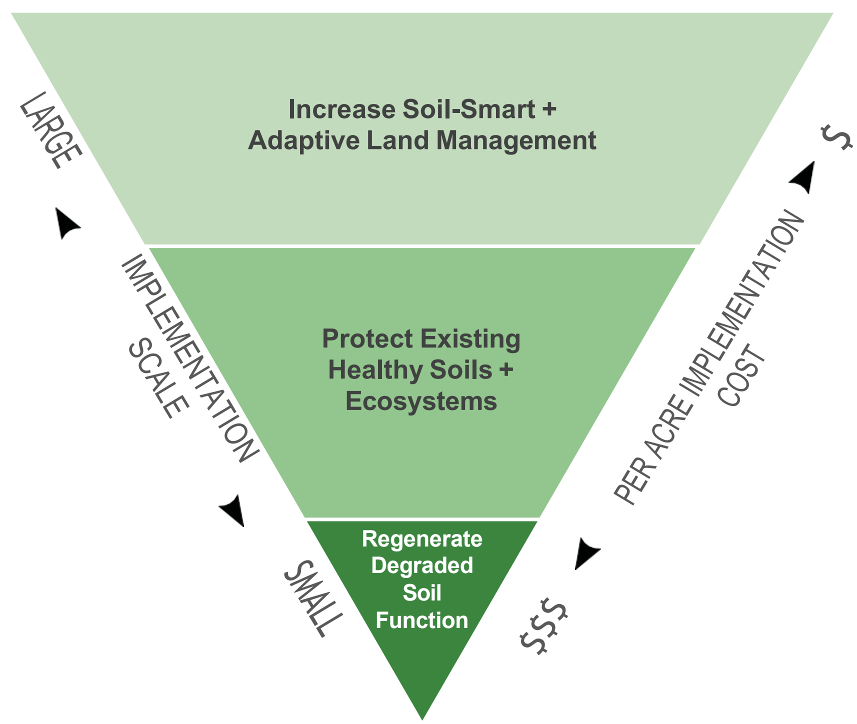
Inherent properties, like soil texture and slope, typically develop over centuries and change only when large disturbances, like landslides or construction projects, remove or add large quantities of material. Dynamic properties—like the level of compaction or concentration of soil organic matter—can and do change more rapidly with changes to land cover and land management.

Broadly speaking, the less frequently and intensely soils and the ecosystems they support are disturbed, the more fully they can achieve their dynamic function potential. This can be seen in the soil organic carbon (SOC) density both within and between land cover types. Soil health is a measure of a soil's dynamic function within the bounds defined by its inherent properties.

Together the actions of this Plan are designed to protect against and reverse the permanent degradation of soil's inherent properties while improving dynamic soil function. These actions include recommendations for changes to Statewide and Municipal policies and programs, greater support for land managers, pilot programs to accelerate the adoption of better management practices, and research to improve the understanding of how soils respond to differential management and the likely effects of climate change.

Each chapter for the five land cover types—forests, wetlands, agriculture, developed open space, and impervious soils—describes, at length, specific actions and strategies to address the vulnerabilities of these soils to climate change and natural hazards, land conversion, and degradation from land management.

Figure 4.1 - Scale and Costs of Implementing Healthy Soils Strategies



Improving soil health in Massachusetts requires the broadscale adoption of soil-smart land management practices, increased protection of existing soil resources and their ecosystems, and the targeted regeneration of soils where they improve ecosystem function and mitigate vulnerability.

Recommendation Summary Matrix

Definition of Readiness and/or Plausibility	
1	**A High rating** is defined as an action that is supported by an existing program or legislation and that was highly supported by the HSAP Work Group.
2	**A Medium rating** is defined as an action for which there is an existing program or legislation but will require some changes for implementation, and that was highly supported by the HSAP Work group.
3	**A Low rating** is defined as an action for which there is not an existing programmatic or regulatory pathway or which was not unanimously supported by the HSAP Work Group.

Strategy	Action	Land Cover Applicability					Readiness/ Plausibility	Scale
		Wetlands	Forests	Agriculture	Recreational + Ornamental	Impervious Dominated		
Limit Land Conversion	Protect the healthy soils at highest risk of conversion by accelerating conservation of vulnerable parcels	√	√	√			*2*	Statewide
	Maintain or increase incentives that keep soils healthy and in supportive land cover.	√	√	√	√		*2*	Statewide
	Expand economic, technical, and additional supports for smart growth planning and policies.		√	√	√	√	*1*	Local/ Statewide
	Seek to direct development toward previously developed and degraded soils.			√	√	√	*1*	Local
	Explore options to improve enforcements, standards, and practices for Wetlands Protection Act compliance and efficacy.	√		√			*1*	Statewide
	Seek to permanently protect 30% of undeveloped prime farmland soils and soils of statewide importance by 2030.		√	√			*3*	Statewide
	Seek to avoid single use solar development on farmland.			√			*1*	Local/ Statewide
	Explore options for support from appropriate state offices (MVP CZM, etc.) to acquire or fund space for wetland migration in coastal areas.,	√	√	√	√	√	*2*	Regional

Strategy	Action	Land Cover Applicability					Readiness/ Plausibility	Scale
		Wetlands	Forests	Agriculture	Recreational + Ornamental	Impervious Dominated		
Restore Functional Capacity of Soils	Regenerate forests and tree cover on abandoned and degraded lands.				√	√	1	Local/ Statewide
	Increase tree cover in highly impervious and urbanized areas to reduce urban heat island effect and improve carbon and water holding capacity.				√	√	2	Local
	Regreen under-used or abandoned impervious surfaces and regenerate soil health on already developed lands					√	1	Local/ Statewide
	Incentivize strategic reforestation along rivers, streams, wetlands and other places where forests provide greater resistance and resilience to climate change induced disturbance.			√	√	√	2	Statewide
	Work to replant a minimum of 500 miles of unforested riparian buffers by 2030.		√	√	√	√	2	Statewide
	Seek to enhance state and local regulations to work in concert to protect the structure and function of wetland soils and the ecosystems they support.	√					2	Local/ Statewide
	Accelerate peatlands restoration on retired cranberry lands	√					1	Regional
	Accelerate proactive mitigation and adaptation measures for sea level rise and other flooding aimed at protecting and restoring soil-based ecosystem services.	√	√	√	√	√	2	Regional

Strategy	Action	Land Cover Applicability					Readiness/ Plausibility	Scale
		Wetlands	Forests	Agriculture	Recreational + Ornamental	Impervious Dominated		
Transform Soil Management Practices	Increase active forest and wetland management that favors future climate adapted species.	√	√				2	Statewide
	Enhance typical development and construction processes to avoid loss of soil health.				√	√	2	Local/ Statewide
	Expand BMPs that emphasize soil health and carbon-informed management.	√	√	√	√	√	1	Statewide
	Incentivize the use of matting and timber bridging in forest harvesting when soils are vulnerable.		√				1	Statewide
	Seek to Improve design standards, regulations, construction practices, and oversight to ensure replication and restoration efforts are effective and successful at creating/regenerating healthy wetland soil conditions.	√					2	Local/ Statewide
	Endeavor to account for impacts to soil health, such as additional carbon emissions, reduced sequestration, or increased sedimentation, when undertaking management activities in wetlands including vegetation management, filling, dredging, or other modifications to hydrology.	√					3	Statewide
	Increase farmer enrollment and participation in existing programs that provide technical assistance, educational opportunities, and material support.			√			2	Statewide
	Reduce economic barriers that make it difficult for farmers to implement healthy soil practices.			√			3	Statewide
	Incentivize integration of trees and other perennial crops into agricultural systems to increase resistance and resilience to more frequent droughts, floods, and extreme weather.		√	√	√		3	Local/ Statewide
	To enhance soil functions increase perennial, shrub, and tree cover and diversity in recreational and ornamental landscapes - where not precluded by functional requirements.				√	√	2	Local

Strategy	Action	Land Cover Applicability					Readiness/ Plausibility	Scale
		Wetlands	Forests	Agriculture	Recreational + Ornamental	Impervious Dominated		
Transform Soil Management Practices	Implement turf and landscape management practices for soil health on state lands.				√	√	1	Statewide
	Seek to Improve the management of developed open space through enhanced laws, policies, and regulations.		√		√	√	2	Local/ Statewide
	Promote protection, management, and restoration strategies that increase biodiversity, ecosystem health, carbon sequestration, and water retention and infiltration on the landscape.	√	√	√	√	√	1	Local/ Statewide
	Promote proactive efforts to enhance soil-based resistance and resilience capacity to climate and natural disturbances in and around developed areas.		√	√	√	√	2	Local/ Statewide
Expand Resources for Soil-Smart Practices	Seek to increase funding for consultants to assist landowners and communities in protecting and managing carbon-rich lands.	√	√	√			1	Statewide
	Accelerate efforts to increase the viability of farm livelihoods.			√			2	Statewide
	Eliminate technical and knowledge barriers to adoption of practices which increase soil health.	√	√	√	√	√	2	Local/ Statewide
	Increase soil health education and outreach strategies for all professionals that play a role in the creation and maintenance of turf and ornamental landscapes.				√	√	2	Statewide
	Provide technical and financial support to managers of large and moderate size impervious areas to establish and maintain green infrastructure.				√	√	1	Statewide
	Develop or update statewide programs that recognize, educate, and incentivize soil health best practices in the developed landscape.				√	√	1	Statewide

Strategy	Action	Land Cover Applicability					Readiness/ Plausibility	Scale
		Wetlands	Forests	Agriculture	Recreational + Ornamental	Impervious Dominated		
Incorporate Soil Based Criteria in Performance Standards	Account for land and soil-based emissions in all climate change policies and actions (incl. forests and wetlands).	√	√	√	√	√	1	Local/ Statewide
	Address soil protection and post- construction soil performance to protect and maximize soil health during and after site development.				√	√	2	Local/ Statewide
	Develop improved specifications for high-performance engineered soils.				√	√	1	Local/ Statewide
	Conduct and support research and development of practices to regenerate, protect, and improve soil health in developed open space.				√	√	1	Statewide
	Support the development of Impervious + Urban Soils Research Programs.				√	√	1	Statewide
Enhance Capacity to Measure Soil Health	Increase support for research into links between land management practices and soil health.	√	√	√	√	√	1	Statewide
	Increase monitoring + research of ongoing changes to soils from climate change	√	√	√	√	√	2	Statewide

Priority Actions

There is still a tremendous amount to learn about how land management and other changes affect soils. However, it is clear that the legacy of land conversion and soil management since colonization has generally degraded most soils across New England. Regenerating the functions and services lost during this period will be a generational endeavor—with aims, actions, and strategies evolving over time as our understanding of soils and environmental conditions evolve. The six actions listed below represent the necessary work of the next 30 years. In this period, soils can play a critical role in mitigating and facilitating adaptation to climate change by increased carbon storage and greater stormwater absorption capabilities.

1- Protect healthy forested soils at the highest risk of conversion by accelerating the conservation of vulnerable forest parcels.

2- Increase and adapt active forest management practices to bolster resistance to degradation from and resilience to climate change.

3- Consider ways to preserve and increase existing soil organic carbon stocks and sequestration capacity, potentially including updating the Massachusetts Wetlands Protection Act.

4- Seek to enroll 50% of existing agricultural production acres in a healthy soils management program by 2030.

5- Continue funding the Healthy Soils Pilot Program that exemplifies healthy soil practice in developed landscapes.

6- Develop post-construction soil performance guidelines focused on water quality, drought resistance, stormwater runoff, soil depth, and carbon content for all site development + construction projects.

Figure 1.6 - Comparison of Annual Soil Carbon Flux in 2050 in Three Scenarios

Business As Usual
Total Net Carbon Flux
632,334 CO2Eqv

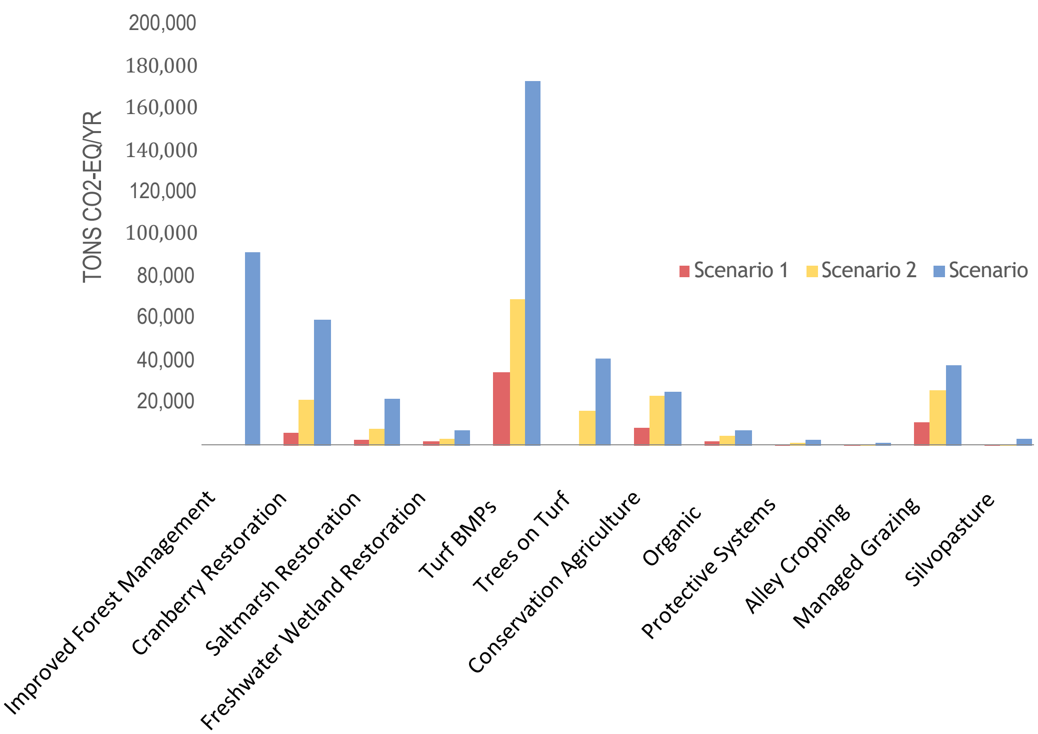
Modest Change
Total Net Carbon Flux
994,479 CO2Eqv

Ambitious Change
Total Net Carbon Flux
1,623,267 CO2Eqv

All three change scenarios examined show that preserving natural carbon sequestration potential by protecting healthy forests and wetlands from land conversion has the greatest benefit. Positive numbers represent gains in soil organic carbon while negative numbers represent carbon emissions.

In addition to these critical statewide actions, the leaders and citizens of Massachusetts' municipalities and institutions can play a role in increasing and better understanding soil health. By taking on the soil management, protection, and regeneration work described in this Plan, they can help create more resilient communities. As the State increases its commitment to climate mitigation and adaptation, programs like the Municipal Vulnerability Preparedness Program may be available to fund this work.

Figure 3.2 - Comparison of Impacts of BMPs on Annual SOC Sequestration in 2050



Better soil management practices have the potential to increase the rate of carbon sequestration. This helps all dynamic functions of soil, especially water infiltration and filtration. Pursuing greater BMP adoption for the turf and lawns of the Commonwealth shows the greatest increase in all scenarios. Accelerated cranberry bog and salt marsh restoration along with carbon-smart forestry practices are other arenas for change that show important potential.

The Healthy Soils Action Plan for Massachusetts is the first of its kind.

By endeavoring to protect, manage, and regenerate soil health across a diversity of ecosystems, land uses, and soil types, this plan lays the groundwork for other states to follow. In the coming years, it will require determined and strategic action from law-makers, land managers, and program administrators to shape effective action with the support of research institutions and observant practitioners.

05 | Glossary

Soil Health Glossary of Terms

Soil Health Terms

aggregate stability
The ability of soil aggregates to resist degradation. An aggregate is many soil particles held together in a small mass. In a “well-aggregated soil” the aggregates and pores between them hold up well to forces such as rain, wind, and compaction.

anthropogenic
Generated by humans. Used to indicate soil conditions, disturbances, or stresses that are created by people.

assessing soil health
Estimating the functional capacity of soil by comparing a soil to a standard such as an ecological site description, a similar soil under native vegetation, a reference soil condition, or quality criteria. The objective of the assessment dictates the standard to be used. (Compare to monitoring.)

attributes of soil change
Quantifiable properties used to describe the nature of soil change, including drivers, types, rates, reversibility, and pathways of change.

available water capacity
Loosely, the amount of water available for plants to use. Specifically, the volume of water released from soil between the time the soil is at field capacity (the maximum water held in soil against the pull of gravity) until the time it is at the wilting point (the amount of water held too tightly in soil for commonly grown crops to extract). Loamy soils and soils high in organic matter have the highest AWC.

bulk density (Db or BD)
The density of soil, i.e., the weight of soil divided by its volume. The BD of agricultural soils normally ranges from 1.0 to 1.6 g/cm3.

cation exchange capacity (CEC)
The capacity of soil to hold nutrients for plant use. Specifically, CEC is the amount of negative charges available on clay and humus to hold positively charged ions. Effective cation exchange capacity (ECEC) is reported for acid soils (pH<5). Expressed as centimoles of charge per kilogram of soil (cmolc/kg).

disturbance
An event or its change in intensity or frequency which alters the structure or functional status of an ecosystem. Examples of disturbances that can affect soil include drought, fire, harvest, tillage, compaction, overgrazing, or addition of pesticides.

dynamic soil properties
Soil properties that change over the human time scale in response to anthropogenic (management, land use) and non-anthropogenic (natural disturbances and cycles) factors. Many are important for characterizing soil functions and ecological processes and for predicting soil behavior on human time scales. (Compare to use-dependent soil properties.)

function
A service, role, or task that meets objectives for sustaining life and fulfilling humanity’s needs and is performed by soil or an ecosystem. (Compare to soil function.)

functional capacity
The quantified or estimated measure of physical and biophysical mechanisms or processes selected to represent the soil’s ability to carry out the function.

human time scale
That portion of the pedogenic time scale that covers periods of centuries, decades, or less.

hydraulic conductivity (Ksat)
A quantitative measure of how easily water flows through soil. (Compare to infiltration and permeability.)

indicator of soil quality
A quantitative or qualitative measure used to estimate soil functional capacity. Indicators should be adequately sensitive to change, accurately reflect the processes or biophysical mechanisms relevant to the function of interest, and be cost effective and relatively easy and practical to measure. Soil quality indicators are often categorized into biological, chemical, and physical indicators.

indicators of soil quality, biological
Measures of living organisms or their activity used as indicators of soil quality. Measuring soil organisms can be done in three general ways: 1) counting soil organisms or measuring microbial biomass, 2) measuring their activity (e.g. soil basal respiration, cotton strip assay, or potentially mineralizable nitrogen), or 3) measuring diversity, such as diversity of functions (e.g., biolog plates) or diversity of chemical structure (e.g. cell components, fatty acids, or DNA). Each approach provides different information.

indicators of soil quality, chemical
These include tests of organic matter, pH, electrical conductivity, heavy metals, cation exchange capacity, and others.

indicators of soil quality, physical
Physical characteristics that vary with management include bulk density, aggregate stability, infiltration, hydraulic conductivity, and penetration resistance.

infiltration rate
The rate at which water enters soil. (Compare to hydraulic conductivity.)

microbial biomass
The total amount of organisms in the soil, excluding macrofauna and plant roots. Microbial biomass is typically determined through substrate-induced respiration, or fumigation-extraction methods.

monitoring soil quality
Tracking trends in quantitative indicators or the functional capacity of the soil in order to determine the success of management practices or the need for additional management changes. Monitoring involves the orderly collection, analysis, and interpretation of data from the same locations over time. (Compare to assessing.)

organic matter
Any material that is part of or originated from living organisms. Includes soil organic matter, plant residue, mulch, compost, and other materials.

organic matter, active fraction
The highly dynamic or labile portion of soil organic matter that is readily available to soil organisms. May also include the living biomass. Particulate organic matter (POM) and light fraction (LF) are measurable indicators of the active fraction. POM particles are larger than other SOM and can be separated from soil by sieving. LF particles are lighter than other SOM and can be separated from soil by centrifugation.

organic matter, stabilized organic matter
The pool of soil organic matter that is resistant to biological degradation because it is either physically or chemically inaccessible to microbial activity. These compounds are created through a combination of biological activity and chemical reactions in the soil. Humus is usually a synonym for stabilized organic matter, but is sometimes used to refer to all soil organic matter.

permeability
The qualitative estimate of the ease with which fluids, gases, or plant roots pass through soil.

porosity
The volume of pores in a soil sample divided by the bulk volume of the sample. Air-filled porosity is the fraction of the bulk volume of soil that is filled with air at any given time or under a given condition, such as a specified soil-water content.

primary ecological processes
Ecological processes including the water cycle (the capture, storage and redistribution of precipitation), energy flow (conversion of sunlight to plant and animal matter), and the nutrient cycle (the cycle of nutrients such as nitrogen and phosphorus through the physical and biotic components of the environment).

processes
Physical, chemical and biological mechanisms that follow fundamental scientific laws. Examples include pedogenic processes, geomorphic processes, and ecological processes.

soil function
Any service, role, or task that soil performs, especially: 1) sustaining biological activity, diversity, and productivity; 2) regulating and partitioning water and solute flow; 3) filtering, buffering, degrading, and detoxifying potential pollutants; 4) storing and cycling nutrients; and 5) providing support for buildings and other structures and to protect archaeological treasures. (Compare to function, functional capacity.)

soil health or soil quality
The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. In short, the capacity of the soil to function. There are two aspects of the definition: inherent soil quality and dynamic soil quality. (Compare to functional capacity.)

soil health, dynamic
That aspect of soil quality relating to soil properties that change as a result of soil use and management or over the human time scale.

soil health, inherent
That aspect of soil quality relating to a soil's natural composition and properties as influenced by the factors and processes of soil formation, in the absence of human impacts.

soil organic matter
The total organic matter in the soil. It can be divided into three general pools: living biomass of microorganisms, fresh and partially decomposed residues (the active fraction), and the well-decomposed and highly stable organic material. Surface litter is generally not included as part of soil organic matter.

soil resilience
The capacity of a soil to recover its functional capacity after a disturbance.

soil resistance
The capacity of the soil to maintain its functional capacity through a disturbance.

soil respiration
The amount of carbon dioxide given off by living organisms and roots in the soil.

soil structure
The arrangement of soil particles into aggregates which form structural units. Size, shape, and distinctness are used to describe soil structure. Farmers often describe soil structure with words such as crumbly or cloddy.

tilth
The overall physical character of soil with regard to its suitability for crop production.

use-dependent or management-dependent properties
Soil properties that show change and respond to use and management of the soil, such as soil organic matter levels and aggregate stability. This is a narrower term than dynamic soil properties which encompasses all changes on the human time scale including those induced by natural disturbances or cycles.

use-invariant properties
Soil properties that show little change over time and are not affected by use and management of the soil, such as mineralogy and particle size distribution.

water holding capacity
The amount of water that can be held in soil against the pull of gravity.

Soil Ecology Terms

aerobic
With oxygen. Aerobic organisms, including animals and most soil organisms, require environments with oxygen. See anaerobic.

anaerobic
Without oxygen. Anaerobic organisms, including some soil bacteria, need oxygen-free environments such as saturated soils. Facultative anaerobes can function as either aerobes or anaerobes depending on environmental conditions. See aerobic.

compost tea
An infusion made by leaching water through compost, sometimes with nutrients added, such as molasses and kelp, to encourage certain organisms. Soluble organic matter and the organisms in the compost are rinsed out of the solid phase and left suspended in the water. This "liquid compost" is easier to apply than solid compost.

decomposition
The biochemical breakdown of organic matter into organic compounds and nutrients, and ultimately into its original components.

denitrification
A process performed by a few species of anaerobic soil bacteria in which nitrite or nitrate is converted to nitrogen gas (N_2) or nitrous oxide (N_2O). Both N_2 and N_2O are volatile and lost to the atmosphere.

diversity
Biological diversity can refer to the number of species in an area, the number of types of species (e.g. microbial functional groups, or plant structural types), the degree of genetic variability within a species, or the distribution of species within an area.

emergent properties
Properties of a whole system that are not apparent from examining properties of the components of the system.

exudates
Soluble sugars, amino acids and other compounds secreted by roots.

food web, soil
The interconnected community of organisms living all or part of their lives in the soil.

habitat
The environment where an animal, plant, or microbe lives and grows.

hyphae
Long chains of cells formed by fungi usually occurring between aggregates rather than within micropores. (Compare to mycelium.)

immobilization
The conversion by soil organisms of inorganic nutrients such as ammonium or nitrate into organic compounds that are part of their cells. This makes the nutrients temporarily immobile in the soil and unavailable to plants. (See mineralization.)

keystone species
A species which, if removed from an ecosystem, causes a dramatic change in the system, and which has been proposed as an indicator of the functional capacity of the system.

lignin
A hard-to-degrade compound that is part of the structure of older or woody plants. The carbon rings in lignin can be degraded by a few fungi.

liverworts
Small non-vascular plants.

microbe or microorganism
An imprecise term referring to any organism too small to see with the naked eye. Generally, "microbes" refers to bacteria, fungi, and sometimes protozoa.

mineralization
The conversion of organic compounds into inorganic, plant-available compounds such as ammonium. This is accomplished by soil organisms as they consume organic matter and excrete wastes. (See immobilization.)

mycelium
A bundle of fungal hyphae that form the vegetative body of many fungal organisms.

mycorrhizal associations
A symbiotic association of certain fungi with roots. The fungi receive energy and nutrients from the plant. The plant receives improved access to water and some nutrients. Except for brassicas (mustard, broccoli, canola) and chenopods (beets, lamb's-quarters, chard, spinach), most plants form mycorrhizal associations.

nitrification
A process accomplished by a few groups of aerobic organisms in which ammonia is converted to nitrite and then nitrate.

rhizosphere
The narrow region around roots where most soil biological activity occurs. Soil organisms take advantage of the sloughed and dead root cells and the root exudates found in this region.

soil ecology
The study of interrelations among soil organisms and between organisms and the soil environment.

trophic levels
Levels of the food chain. The first trophic level includes photosynthesizers that get energy from the sun. Organisms that eat photosynthesizers make up the second trophic level. Third trophic level organisms eat those in the second level, and so on. It is a simplified way of thinking of the food web. In fact, some organisms eat members of several trophic levels

Glossary adapted from the USDA Soil Health Glossary, https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/?cid=nrcs142p2_053848. Accessed 1/14/21

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